INFLUENCE OF NUTRIENT AND LIGHT MANAGEMENT ON POSTHARVEST QUALITY OF LETTUCE (*LACTUCA SATIVA L.*) IN SOILLESS PRODUCTION SYSTEMS

by

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DECLARATION

By submitting this thesis/dissertation electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the authorship owner thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Tonderai Clive Mandizvidza

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Summary

Despite the ease in manipulating plant growth and development variables, meticulous management is required to achieve high yields and good quality crops in a soilless system. A deep understanding of the intricacies involved in plant growth and development will aid in optimizing these variables to achieve desired yield and crop quality with subsequent effect on postharvest quality. Therefore manipulating and managing plant growth and development variables should be considered as pivotal in a soilless production system. For that reason, other techniques such as foliar fertilization have been employed in an attempt to enhance crop growth and development during production to increase productivity and crop quality. The aim of this study was to assess how manipulation and management of nutrient solutions (different cation concentrations), light intensity levels and foliar fertilization in a hydroponic system affect postharvest quality. The study on nutrient cation concentrations was conducted in a tunnel whilst light intensity study was conducted in a controlled glasshouse at the University of Stellenbosch in the Western Cape Province of South Africa.

To evaluate the effect of light intensity levels, two lettuce types (cos and iceberg) were exposed to three different light intensities, control of 450 µmol $m^{-2}s^{-1}$ (19.44 mol $m^{-2}d^{-1}$), 60% of control at 270 µmol $m^{-2}s^{-1}$ (11.66 $m^{-2}d^{-1}$), 40% of control at 180µmol $m^{-2}s^{-1}$ (7.78 $m^{-2}d^{-1}$). Overall visual appearance was considered using plant height (mm) and cos lettuce reaching significant height at 60% and 40% LI. A significant interaction was observed with regards to texture parameter with cos lettuce generally outperforming iceberg.

In the second trial, nutrient solutions with different cation concentrations were evaluated. Two lettuce types (cos and iceberg) were cultivated hydroponically with nutrient solutions containing Ca^{+2} as 45% of the total cations (S 1) compared to low Ca^{+2} of 20% of the total cations (S 2) and high Ca^{+2} of 60% of the total cations (S 3) all at an EC of 1.30 mS cm^{-1}. Based on the nutrient composition, the increase or decrease in cation concentration affected the uptake of nutrients with adverse effects on nutritional values of crops. Variation was largely due to nutrient availability at different concentrations for plant absorption and use.

Lastly, foliar fertilization of Ca based boron, nitrogen and silicate sprays on rocket and red oak lettuce revealed interactions between the foliar treatments (CaN, CaB and CaSi) and plant types (red oak lettuce and rocket) on the fresh weight (yield) of plants grown hydroponically and differences in means with regard to total moisture and weight loss were also observed for treatment and crop variety effect.

The results in this thesis make a valuable contribution to our understanding of manipulating and management of soilless production system with adverse effects on postharvest.

Opsomming

Ten spyte daarvan dat dit relatief maklik is om die groei en ontwikkeling van plante te manipuleer in ʼn grondlose stelsel is noukeurige bestuur steeds nodig ten einde 'n hoë opbrengs en 'n goeie kwaliteit gewasse te verkry. ;n Goeie begrip van die kompleksiteit betrokke by groei en ontwikkeling van plante sal help met die optimalisering van hierdie veranderlikes om sodoende die oesopbrengs en kwaliteit te verbeter. Daarom is dit uiters belangrik om plant groei en ontwikkeling noukeuring te manipuleer en te bestuur in 'n grondlose produksie stelsel. Om dié rede word ander tegnieke soos blaartoediening van nutriente tydens produksie gebruik in 'n poging om groei en ontwikkeling en kwaliteit te verbeter. Die doel van studie was om te bepaal hoe manipulasie en bestuur van voedingsoplossings (verskillende katioon konsentrasies), ligintensiteit en blaar bemestingspeile in 'n hidroponiese stelsel na-oes gehalte beïnvloed. Die studie oor voedingstowwe katioon konsentrasies is uitgevoer in 'n tonnel terwyl die ligintensiteit studie uitgevoer in 'n beheerde glashuis by die Universiteit van Stellenbosch in die Wes-Kaap Provinsie van Suid-Afrika.

Om die effek van ligintensiteit vlakke op twee blaarslaai kultivars (cos en ysberg) te evalueer is plante blootgestel aan drie verskillende ligintensiteite; ʼn kontrole van 450 mol $m^{-2}s^{-1}$ (19.44 mol $m^{-2}d^{-1}$), 60% van die kontrole, 270 umol $m^{-2}s^{-1}$ (11.66 $m^{-2}d^{-1}$), en 40% van die kontrole teen 180µmol $m^{-2}s^{-1}$ (7.78 m $m^{-2}d^{-1}$). Algehele visuele voorkoms is geassesseer deur planthoogte (mm) te bepaal en cos slaai wat ʼn beduidende toename toon by 60% en 40% ligintensiteit behandelings. 'n Beduidende interaksie is waargeneem ten opsigte van tekstuur as kwaliteit parameter waar oor die cos slaai beter gevaar het as ysberg slaai.

In die tweede stel proewe is voedings oplossings met verskillende konsentrasies (katioon konsentrasies) geëvalueer. Twee blaarslaai kultivars (cos en ysberg) is hidroponies verbou. Voedingsoplossings waar Ca^{+2} 45% van die totale katione opmaak(S 1) teenoor ʼn oplossing waar Ca^{+2} slegs 20% ot die total katione opmaak (S 2) en ʼn oplossing waar Ca^{+2} 60% van die totale katione opmaak (S 3) almal teen 'n EG van 1.30mS cm^{-1} is toegedien. Op grond van die voedingstof samestelling het ʼn toename in die katioon konsentrasie die opname van voedingstowwe geaffekteer wat ʼn nadelige uitwerking op voedingswaarde van gewasse gehad het. Dit was waarskynlik grootliks te wyte aan die variasie op die beskikbaarheid van voedingstowwe vir plante asook die opname van elemente.

Laastens, blaar bemestings van Ca, Boor, stikstof en silikaat bespuitings getoets op slaai in ʼn hidroponiese sisteem. ʼn Interaksies tussen die blaarbespuitings (CaN, CaB and CaSi) en planttipes ten opsigte van die vars gewig (opbrengs), en vogverlies na-oes is aangeteken.

Die resultate in hierdie tesis lewer 'n waardevolle bydrae tot ons begrip van hoe om gewasse te bestuur en te manipuleer ten einde opbrengs en kwaliteit te verbeter.

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CHAPTER 1

INTRODUCTION

The quest to grow any crop at any given time of the year without limitations and restrictions of weather, soil and landform has been one of the most significant scientific milestones achieved over recent years. This has allowed for more research of which results have been integrated into protected crop production systems such as hydroponics that is now a widely and frequently used technique according to Savvas (2003). This technique allows growing of plants without soil and for providing a considerable degree of control of the elemental environment surrounding the plant roots (Jones Jr. 1982). Knowledge of plant growth variables and the ability to manipulate them has been at the forefront of this system. Therefore it is crucial to understand the undertakings of the system and how it can be made viable, pragmatic and considering the adverse effects on post-harvest quality. Post-harvest is a crucial stage in agro-processing and has a huge impact on the farmer as it determines whether his crop is marketable or not. Understanding the implications of controlled crop production environments on post-harvest quality is therefore crucial in aiding the farmer to achieve desired market standards, without compromising on yield (Coolong 2012).

Studies on plant growth and development have shown essential variables including plant nutrition, climatic elements such as light, rainfall and humidity. Therefore the controlling of such variables in hydroponic systems is to be carried out meticulously (Brechner 1996). Optimization of these variables has been made possible through cultivation in hydroponic systems with benefits beyond increased biomass in a sustainable way (Benton Jones Jr. 2004). The key aspects to a successful hydroponic system have been thoroughly researched. These include the type and properties of the growth medium (which is a soilless medium), fertigation management and the regulation of temperature, humidity and light intensity to optimize plant growth and development while increasing plant yield and reducing stress caused by drought, pests and diseases (Jensen 2013). Despite numerous research on how the system operates, it is necessary to note the resistance of South African farmers in adopting this technique and more over the growing concern on whether the crops from such a system can be of similar quality to those cultivated in open field systems. Researchers Santos and Ocampo (2005) noted that hydroponics appeared to be a popular and acceptable solution for production under conditions of space restrictions or unavailability of soil. In South Africa neither is necessarily restricted, therefore there is a need to show the benefits of the system in comparison to open field production.

It is necessary to understand that the ability to precisely control nutrient application in hydroponics, compared to open field production, aids in better nutrient uptake and nutrient use efficiency by plants (Adams 1992). This also correlates with climatic variables and has an impact on the yield and nutritional quality of the crop. Research looking at the two cropping systems by Barbosa et al. (2015) has shown to a greater extent the increase in land, water and energy use efficiency of hydroponics in comparison to open field production. It is crucial to note that the crop production systems in their study were not significantly different from each other. However, further research is needed focusing on how production methods affect the post-harvest attributes. Therefore, the aim of this study was to examine how hydroponic crop production practises affect the yield and post-harvest quality of lettuce and how this compares to lettuce from open field production. To achieve this, the following factors were investigated in more detail in a series of trials:

- The effect of nutrient solution management.
- The effect of light intensity management.
- The effect of nutrient foliar applications.

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Chapter 2

LITERATURE REVIEW

2.1 Background

South Africa’s agricultural sector is characterized by two main streams, a modern commercial farming sector and an agro-processing sector and according to AgriSETA (2010) a dualistic agricultural sector. Mahlangu and Toit (2011) stated that agricultural productivity in South Africa can be traced back from 1910. Several authors such as Thirtle et al (1993), Nin et al (2003), Conradie et al (2009), and Liebenberg et al (2012) have had interest in measuring agricultural productivity over the years. However, a surgical look at the diversity of the commercial farming landscape in South Africa will invite a deeper understanding and analysis of the farming systems environment. Furthermore, commercial farming in South Africa can be further dissected into different agro-climatic zones as shown in figure 1. noted by Benhin (2006), which govern the types of farming operations thereof (Goldblatt 2011).

Other reports by AgriSETA (2010) and the Department of Agriculture, Forestry and Fisheries (2012), show that commercial farming is further divided according to activities such as field crop husbandry, horticulture and lastly animal production. These operations are practiced in different agro-climatic zones best fitting them as noted by Benhin (2006) on medium to large scale farms, either on commercial or subsistence level.

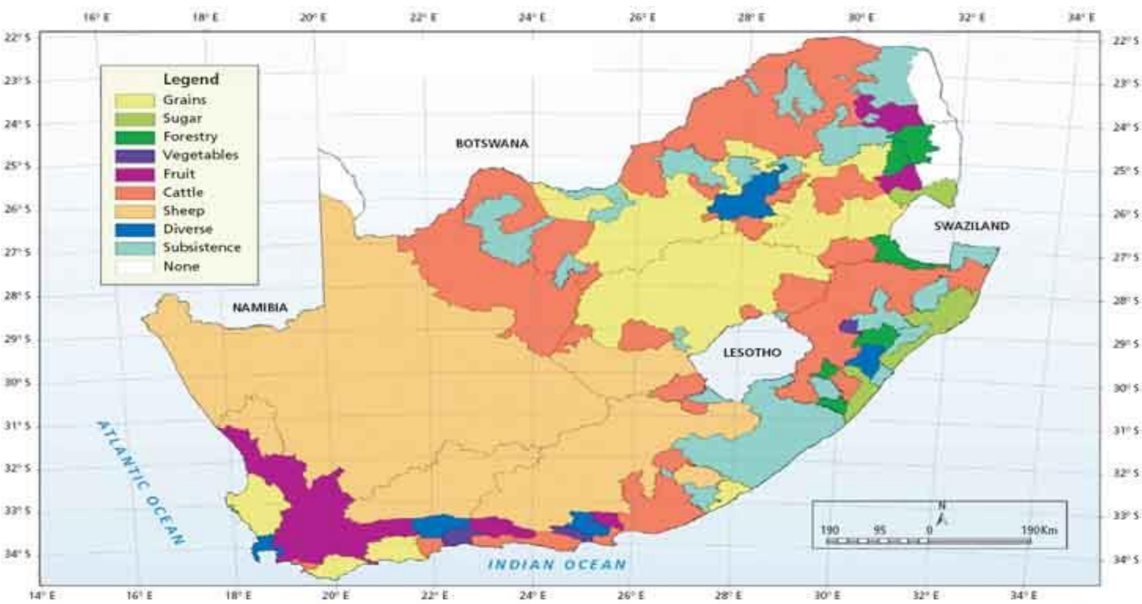

Figure 1: Agricultural Regions of South Africa, Source: FAO corporate document repository.

Over the years agricultural productivity has been easily quantified largely due to the different crop production systems found in the agro-ecological zones of South Africa (Figure 1). Therefore development of different farming systems is solely on the basis of combinations of soil, landform and climatic characteristics which influence the types of crop production methods and techniques as well as types of crops suitable for production in those zones.

2.1.1 Agro-climatic zones on types of farming practices

Goldblatt (2011) stated that farming activities range from intensive crop production in the winter rainfall and high summer rainfall areas, to cattle ranching in the bush veld and sheep farming in the more arid regions. Climate and soil combinations leave only 12% of the country suitable for the production of rain-fed crops and only 3% considered truly fertile land (AgriSETA 2010). Most of South Africa's land surface (69%) is suitable for grazing and livestock farming and is by far the largest agricultural sector in the country. Benhin (2006) noted that the availability of rainfall in South Africa has been the greatest limiting factor in agricultural productivity. This has led to different farming systems being suited to the rainfall distribution patterns and soil structures.

2.1.2 Agro-climatic zoning implications

Adaptation of farming systems to the ever changing agro-climatic zones has resulted in intensified conventional farming methods. Cassman and Pingali (1995) found that conventional or commercial intensification practice allowed farmers to maximize yields per unit time and area by planting more crops each year specializing in repetitive cultivation of modern varieties and using higher amounts of external inputs. This was achieved using methods such as monoculture, continuous cropping, conventional tillage, and cultivation in fragile hillside areas. According to Killebrew (2010) and Walls (2006) the methods pose a negative threat to the ecosystem such as a decline in soil fertility, reduced soil organic material, increased erosion and reduced habitats for insect and wildlife.

2.2 Possible mitigation of adverse implications of agro-climatic zoning on conventional farming methods

Mitigation of adverse effects of agro-climatic zones on conventional farming practices has seen the integration of sustainable farming methods. This will not only conserve and preserve the environment but also be able to bypass the agro-climatic limitations across the country, thus enabling crop farming in arid areas, maximizing yield as well as land and water use, while possibly producing the same if not better quality crops (Benton Jones Jr. 2004).

Possible mitigation such as the integration of commercialized hydroponics in conventional farming systems should aid in crop management and improve conventional farming methods (Benton Jones Jr. 2004). There is the need to first understand that hydroponics is a sub-system of conventional farming, when integrated can be a mitigating measure against climatic limitations and conventional farming practices that are harmful to the ecosystem, quality and yield of crop produce (Wattanapreechanon and Sukprasert 2012).

According to Savvas (2003), commercial hydroponics is a modern technology involving plants grown in inert media substituting soil, in order to uncouple the performance of the crop from problems associated with the ground, such as soil-borne diseases, non-arable soil, and poor physical properties. Both (2003) highlighted the benefits of hydroponic agriculture are numerous. In addition to higher yields and water use-efficiency, when practiced in a controlled environment, hydroponic systems can be designed to support continuous production throughout the year (Brechner 1996; Wattanapreechanon and Sukprasert 2012).

2.2.1 Hydroponic farming system

Hydroponic systems are versatile and can range from rudimentary backyard setups to highly sophisticated commercial systems. Barbosa et al. (2015) found that various commercial and speciality crops can be grown using this system including tomatoes, cucumbers, peppers, eggplants, strawberries, and many more. Leafy vegetables, such as lettuce can also be grown hydroponically and perform best using the nutrient film technique (NFT) (Brechner 1996). The application of soilless production systems has come as an alternative to the conventional open field production methods and a solution to the adverse effects of agro-climatic conditions.

According to Jensen (2013), hydroponic systems are categorized as open (once the nutrient solution is delivered to the plant roots and it is not reused) or closed (surplus solution is recovered, replenished, and recycled). Swaney (1940) shows the earliest patents of a hydroponic system or soilless cultivation device he created and which over the years has been improved significantly by other inventors like Lusignan (1986) and Blackford (1995) (Figure 2).

When integrated with greenhouses, hydroponics is highly productive, sustainable in terms of water and land use, and protective of the environment (Jensen 2013).

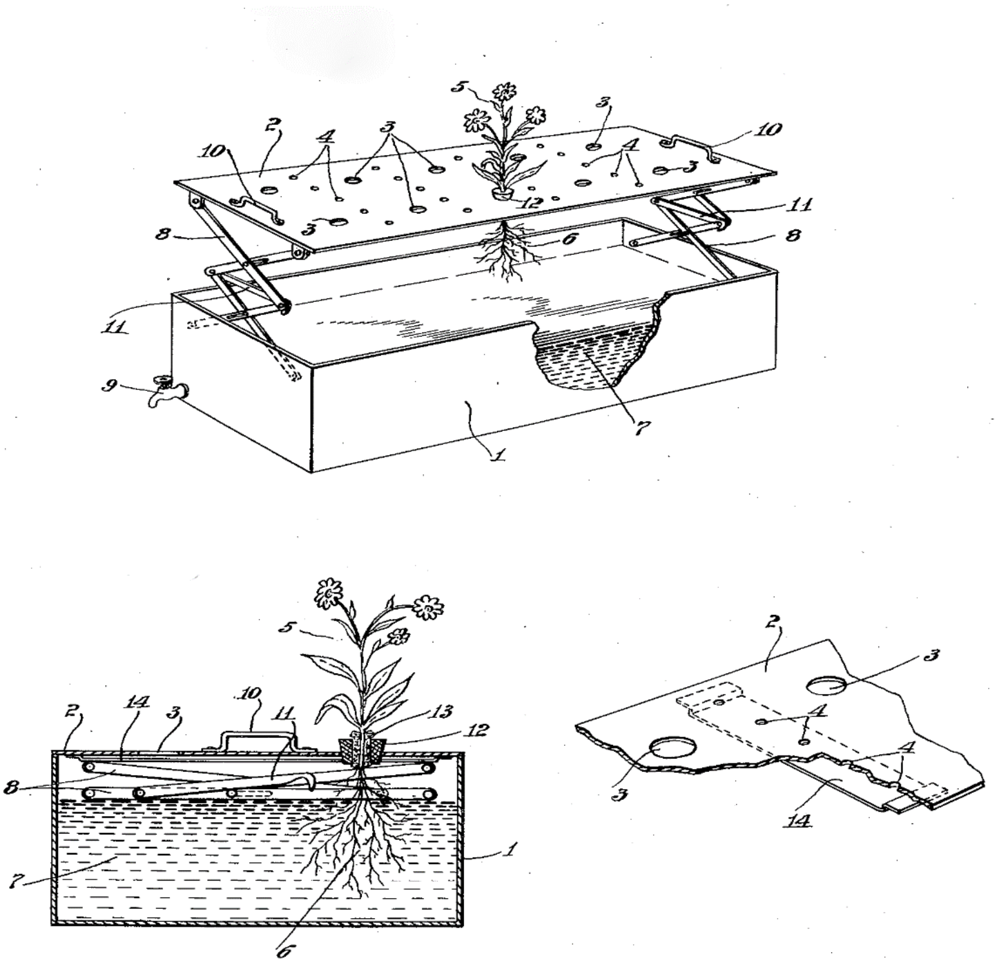

Figure 2: Earliest patent of a hydroponic NFT system.

Many benefits observed during laboratory research applications have seen it over the years developed into a fully-fledged practical farming technique with benefits that outweigh open field crop production techniques (Barbosa et al. 2015). The ability to deliver adequate nutrients for efficient uptake and use by plants through controlled irrigation, optimization of temperature, light and humidity allowed for a larger scale application, which over the years have been developed and to date are computerized to optimize plant growth, development and post-harvest quality. (Savvas 2003).

2.2.3 Hydroponic techniques

According to Swaney (1940) the purpose of his invention was to enable various systems of cultivation without soil to be applied and combined to enable plants to be continuously or intermittently fed with nutrient solution in a structure occupying extremely little space. Fundamentally so, this system has been integrated on a commercial scale as an alternative to soil based cultivation. Albaho et al. (2008) used a technique of hydroponics known as nutrient film technology (NFT). The system operates by running a thin film of nutritive fluid onto plant roots. This process has been favourable, commonly adopted and applied in hydroponics making it an integral technique. The understanding of how to efficiently deliver nutrients for effective uptake by plants also led to development of different types of hydroponics based on a combination of nutrient delivery systems and greenhouse hardware (Brechner 1996). According to Both (2003) and Benton Jones Jr. (2004) the techniques commonly used in these controlled environment systems are static solution cultures where plants are grown in containers of nutrient solution. Brechner (1996) furthermore stated that a nutrient solution must constantly flow past the roots. Lakkireddy et al. (2012) experimented using aeroponics where roots were continuously or discontinuously kept in an environment saturated with fine drops (a mist or aerosol) of nutrient solution. Lastly in ebb and flow also known as flood and drain sub-irrigation, in which there is a tray where plants float above a reservoir of nutrient solution (Coolong 2012). Figure 3 illustrates a modern commercial hydroponic NFT systems.

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Figure 3: Green Drop Farm, Commercial hydroponic system, 2016. Photo courtesy of Tonderai Clive Mandizvidza

2.2.4 Lettuce production

Lettuce is a member of the Asteraceae family, which commonly used is a desired ready to eat leafy vegetable and produced hydroponically (Both 2003; Coolong 2012). The most common types of lettuce grown hydroponically are loose leaf, butter head, and romaine (cos). Other leafy greens, sometimes used to compliment a lettuce selection, include bok choy, spinach, and Swiss chard (Coolong 2012). Lettuce is a cool weather annual crop tolerant to winter cold and light frost, which varies among types such as loose leaf lettuce, butter head lettuce, cos (romaine) lettuce, butter crunch lettuce, Batavian lettuce, heading lettuce and lastly Chinese lettuce grown extensively in temperate and subtropical regions around the world (Mou 2008). Characteristically, the most favourable temperatures for optimum growth and development are daily means between 15°C and 18°C, with monthly means between 7°C and 24°C. Day temperatures ranging from about 17°C to 27°C, and night temperatures between 2°C and 12°C (Both 2003). According to Mou (2008), many heading types will produce only small, inferior heads under hot summer conditions. Certain diseases are more prevalent in hot weather especially in young plants and may also induce this annual crop to bolt. Therefore, temperature and cultivar type are probably the most important factors affecting the success of lettuce production. Researchers Both (2003); Sikawa and Yakupitiyage (2010); Barbosa et al. (2015) recommended hydroponics as a better production method. Field cultivated lettuce requires fertile loam soils supplied with organic matter for best results though fairly tolerant of soil types with its shallow root system it can be grown quite successfully on relatively shallow soils (Sanchez 2000). Figure 4 illustrates overall lettuce production and sales in South Africa and its significance as an economically viable crop to produce.

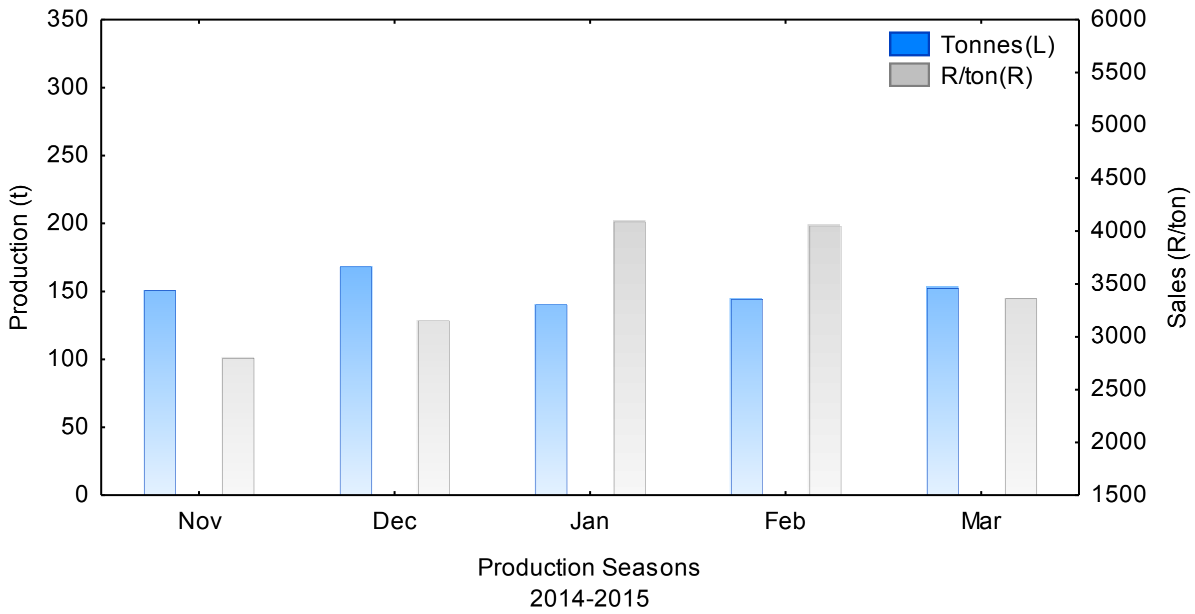

Figure 4: Lettuce production and sales overview for South Africa for the period 2014-2015

2.3 Hydroponics vs conventional open field cultivation

Research has shown the benefits of hydroponics over open field cultivation (Barbosa et al. 2015). Palermo et al. (2012) stated that hydroponic cultivation allows for the control of environmental conditions. This control gives premise that hydroponic cultivation is no-less pragmatic in production of crops in comparison to open field. The use of hydroponic systems over the years since its inception has resulted in its integration in commercial farming landscapes. Barbosa et al. (2015) conducted a comprehensive comparison of the two cultivation systems with regards to land, water and energy requirements. Conventional agricultural practices can cause a wide range of negative impacts on the environment. “Conventional” or “modern industrial agriculture” has been defined as the practice of growing crops in soil, in the open air, with irrigation, and the active application of nutrients, pesticides, and herbicides (Killebrew 2010). Some of the negative impacts of conventional agriculture include the high and inefficient use of water, large land requirements, high concentrations of nutrients and pesticides in runoff, and soil degradation accompanied by erosion (Walls 2006).

Benefits of hydroponic agricultural systems are numerous. In addition to higher yields and water use efficiency, when practiced in a controlled environment hydroponic systems can be designed to support continuous production throughout the year (Brechner 1996). Barbosa et al. (2015) from their research to determine whether hydroponic lettuce production is a suitable and more sustainable alternative to conventional lettuce production in Arizona, found that in terms of yield per area, the hydroponic production of lettuce was 11 ± 1.7 times greater than that of its conventional equivalent. Likewise similarly assessing water consumption their results showed that water consumption between the hydroponic and conventional production was comparable on an area basis, but when normalized by yield the average was 13 ± 2.7 times less water demand in hydroponic production compared to conventional production (Barbosa et al. 2015). Hydroponic lettuce production also had an estimated water demand of 20 ± 3.8 L/kg/y, while conventional lettuce production had an estimated water demand of 250 ± 25 L/kg/y. However, results for energy consumption found that the hydroponic production of lettuce in Arizona requires 82 ± 11 more energy per kilogram produced than the conventional production. Dominating the hydroponic energy use were the heating and cooling loads at 74 000 ± 10 000 kJ/kg/y, followed by the energy used for the supplemental artificial lighting at 15 000 ± 2100 kJ/kg/y. The circulating pumps contributed the least to the total energy use at 640 ± 120 kJ/kg/y. In total, the hydroponic energy use was calculated to equal 90 000 ± 11 000 kJ/kg/y (Barbosa et al. 2015). Despite the energy requirements being specific to Arizona, the results clearly indicate the overall benefits of hydroponic systems in terms of crop yield as well as water and nutrient use efficiency to be much more ideal. The production benefits of hydroponics also extend further to post-harvest quality over those of open field cultivated crops. Hydroponics has been further studied and developed for better delivery of the nutrients in their right quantities as well as efficient and effective use by crops in a sustainable practice (Benton Jones Jr. 2004). Methods like nutrient foliar applications as a supplemental nutrient delivery technique have also been employed and applied in hydroponic crop cultivation systems to increase plant nutrient uptake and use (Pardossi et al. 1999).

2.3.1 Effects of soilless cultivation on postharvest quality in crops

An understanding of the post-harvest stage, particularly disorders and diseases in crops, not only aids in the assessment of quality of produce, but also assist in looking and identifying the adverse effects of the pre-harvest production techniques and how to optimize them. Research undertaken by Both (2003) has recommended optimal climatic conditions for a hydroponic system that will reduce the incidence of tipburn occurrence in lettuce, which occurs mainly on plant leaves if humidity is not controlled accurately. (Collier and Tibbitts 1982) stated that soilless cultivation allowed for a simpler, cost effective and environmentally friendly rectification process, since all variable were controllable within the hydroponic system (Coolong 2012). Achieving market standards set for post-harvest quality for any crop can be done through adjustments of plant growth and development variables during crop production. Hydroponics has revolutionized this ability since all variables can be controlled at any given time during the plant growth and development cycle (Benton Jones Jr 2004). Furthermore, Coolong (2012) explains how hydroponically cultivated lettuce can be harvested with the roots attached which could extend the post-harvest storage life of up to 2 to 4 weeks under the proper storage condition. Therefore, the necessary measures can be implemented in a hydroponic system at any stage of crop production to enhance post-harvest crop quality.

Research comparing post-harvest quality of crops from both hydroponics and conventional cultivation systems have been investigated. Manzocco et al. (2011) found that both systems if not optimized accordingly the disadvantages however could be easily and largely counterbalanced in a hydroponic system through supplementing of specific nutrient for a specific effect.

Palermo et al. (2012) investigated whether soilless cultivation improves the nutritional quality of soybean and its products. They believed hydroponic soybean cultivation could provide proteins and oil under controlled environmental conditions which would be affected in conventional farming by climatic conditions. Results from their research demonstrated that, independent from the cultivar, hydroponic cultivation compared to soil cultivation promoted the accumulation of fats (from 17.37 to 21.94 g/100 g dry matter) and total dietary fibre (from 21.67 to 28.46 g/100 g dry matter) whereas protein concentration were unaffected (Palermo et al. 2012).

Apart from research on the effects of conventional and hydroponic cropping systems on crop nutrition, further research has been carried out to investigate the adverse effects of controlled systems on the post-harvest quality parameters and shelf life of designated crops. Brechner (1996) noted hydroponic variables that affected post-harvest quality to include temperature of the greenhouse air and nutrient solution, relative humidity (RH) and carbon dioxide concentration (CO_2) of the greenhouse air, light intensities from sunlight and supplemental lighting, pH, dissolved oxygen (DO) levels, and electrical conductivity (EC) of the nutrient solution. If not correctly monitored and controlled these variables could impact the yield and quality of crops (Libia et al. 2012). Soilless cultivation in controlled environments involves temperature being regulated by the use of cooling fans and opening of vents, relative humidity (RH) by use of extractor fans and wet walls (Paull 1999). These have a significant effect at post-harvest if not optimized. Too high or low temperature and humidity results in an inefficient uptake of essential nutrients which results in the occurrence of tipburn and other nutrient disorders whilst humidity will further promote fungal spores (Collier and Tibbitts 1984). Light intensity is optimized by either shading or use of supplemental lighting (Ohashi-kaneko et al. 2007; Fu et al. 2012) and if not controlled in terms of daylight, will result in lower crop yield, pigment content reduction which affects the visual appearance (colour, shape and head formation) (Ohashi-Kaneko et al. 2007). Hilton et al. (2009) further investigated the influence of agronomic factors on the visual quality of field-grown lettuce and concluded that based on scientific evidence, improved protocols for the management of raw materials have the potential to extend the quality and shelf-life of minimally-processed leaf material.

2.4 Postharvest quality parameters

Postharvest quality can be analysed further to better understand the causes. The aspect of quality is highlighted as an agro-processing phenomenon which dictates to farmers, the market expectations of standards and minimum crop quality requirements (Tan 1997). Therefore, it is pivotal to recognize the significance of postharvest quality and how different cultivation methods affect this phenomenon. Looking at a widely cultivated hydroponic crop such as lettuce it was proposed that postharvest quality evaluations should not be overlooked but are important tools of this industry. Furthermore improved evaluation methods could result in economic gains by providing the industry with the information necessary to make sound decisions concerning the commodity's maturity for harvest, health and stress at harvest, and shelf life (Scofield 1999). The evaluation process to determine the postharvest quality of crops is carried out by means of a grading tool. Wang et al. (2005) stated that leafy green crops are valued not only for their leaf form and size but also their greenness and this is primarily done visually, which makes it subjective and prone to biases from appraisers and quality controllers.

2.4.1 Overall visual quality

Visual quality is the first and foremost postharvest criterion applied in the grading and assessment of crop quality at harvest and is key to marketability and economic viability of the produce (Mditshwa et al. 2015). Visual grading allows produce to be assessed and graded to meet market and consumer satisfaction. According to literature, visual grading can be done for various reasons such as detecting physiochemical abnormalities, which affect crop appearance and conducted either objectively, subjectively or together, which are different tools of assessing overall visual quality. Objective assessment uses high-tech visual equipment to detect defects, size and shape and sorts accordingly. On the other hand subjective assessment involves the use of a sensory panel of accredited quality assessors to grade or score accordingly (Zhou et al. 2004). However, the application varies according to crop type and market quality needs.

It is therefore crucial to apply precise tools and methods to meet desired market standards and not compromise on quality, which stems from the pre-production of the produce to the quality assessment at harvest (Pace et al. 2014). Recently, leafy vegetables have become a highly desired, ready to eat product, and primarily lettuce (Zhou et al. 2004). Therefore, it becomes significantly important not to overlook visual quality parameters. Research to date has been carried out to identify the best methods to use when looking at overall visual quality and a correlation has been shown with fresh weight (moisture content) and chlorophyll content as some of the key characteristics for either objective or subjective measurements (Agüero et al. 2008). Overall visual quality is largely affected by the type of farming method and other pre-crop production variables such as light intensity which promotes photosynthesis and development of chlorophyll, nutrient solution management which allows for efficient uptake of essential elements like Ca, N, Si and B which are responsible for overall visual quality (Brechner 1996) . Scientific and technical advances have allowed the application of more objective tools in the assessment of overall visual quality at postharvest (Wang et al. 2005; Pace et al. 2014). A descriptive loss of quality (LOQ) scale ranging from 1 to 5 scored by panellists and found that lettuce incubated at 4°C had better quality compared to lettuce stored at 10°C and when compared to a more objective technique that applied image analysis of percent brown area, the authors found similar results as obtained by panellists (Zhou et al. 2004). Therefore both objective and subjective methods to date can aid as overall visual quality assessment tools. Overall visual quality/appearance parameters entail various attributes set by quality assessment boards and institutes for food science. Table 1 shows the visual quality parameters considered for different crops according to Tan (1997), whilst table 2 shows different diseases and disorders that affect the visual appearance of commonly produced hydroponic crops.

Table 1: Basic overall visual quality parameters according to Tan (1997)

CROP TYPE	OVERALL VISUAL QUALITY		
	OVERALL APPEARANCE	TEXTURE	COLOUR
LETTUCE	• Fresh appearance • Developed heads	• Firm • Crisp	• Uniform green typical of the variety
CUCUMBER	• Intact • Fresh • Sufficiently developed	• Firm	• Green coloring typical of the variety
TOMATOES	• Intact • Sound • Regular shape	• Firm • Glassy appearance	• Color typical of the variety

Pace et al. (2014) noted that more research on the appearance aspect has been carried out and a five point quality rating scale has been the method applied by several authors to estimate overall appearance where a grading scale from 5: which denotes excellent, to 1: which denotes extremely poor is used as an estimate of visual quality and dependant on subjective judgement.

Table 2: Common post-harvest disorders and diseases that affect overall visual quality according to Tan (1997)

CROP TYPE	OVERALL VISUAL QUALITY	
	DISORDERS	DISEASES
LETTUCE	• Russet spotting • Tipburn • Marginal browning • Pink rib	• Bacterial soft rot • Grey mold • Downy mildew • Watery soft rot
CUCUMBER	• Wilting • Chilling injury • Yellowing	• Anthracnose • Bacterial soft rot • Bacterial spot • Rhizopus rot
TOMATOES	• Chilling Injury • Heat injury • Regular shape	• Bacterial soft rot (Erwinia) • Rhizopus rot

It is crucial to note that the loss of overall visual quality aspects of crops are to a large extent caused by adverse effects of mismanaged pre-harvest methods and techniques used (Ferguson et al. 1999). The common and most problematic disorders and diseases associated with the loss of overall visual quality is wilting in cucumbers, where they quickly become flaccid and shrivel at the blossom end, unless they are under high relative humidity (e.g. RH>90%). Another commonly prominent disorder is tipburn found on lettuce leaves which results in a breakdown of leaf margins due to high temperatures and light intensity conditions during growth near maturity resulting in localized calcium deficiency in leaves or leaf margins (Tan 1997; Chiloane 2012). These occurrences resulted in vast research being conducted on how to reduce the incidences of these disorders and diseases on harvested produce. Research has been conducted on pre-harvest and postharvest handling techniques to improve quality and shelf life of produce, a measure against postharvest diseases and disorders (Tan 1997; Kader 2000; Passam et al. 2007). Another measure since the crop undergoes a storage period from harvest till it reaches the consumer involves modified atmosphere packaging (MAP) material which according to Martinez-Sanchez et al. (2011) inhibits gaseous exchange to extend shelf life and maintain visual quality, with all other variables such as temperature and light intensity steadily maintained during storage (Liu 2008; Gutiérrez-Rodríguez et al. 2012).

2.4.2 Shelf life

Another crucial postharvest parameter with significant effect to marketability is shelf life. Hilton et al. (2009) noted the biggest concern regarding ready to eat, cut salads is its limited shelf-life, largely due to discolorations at the cut surfaces causing post-processing quality loss (López-Gálvez et al. 1996). The overall visual quality aspects are particularly critical because they impart a shelf life duration to the product, which is often not consistent with the needs of actual delivery systems (Manzocco et al. 2011). Furthermore, from their study they found significant factors correlating to loss of shelf life such as the increase in browning during storage which lowered the overall visual appearance affecting the shelf life. Similar investigations by Bolin and Huxsoll (1991) revealed limiting anatomical and physiological phenomenon that also affected the shelf life of lettuce which were largely attributed to postharvest treatments for storage purposes such as cutting, which ruptures plant cells and cell wall influencing chemical reactions that reduce storage life. Further research found other factors such as light levels, temperature, moisture content, carbon dioxide and oxygen exchange as primary factors responsible for either enhanced shelf life or reduced shelf life since light levels influence photosynthesis and gaseous exchange during storage (Martinez-Sanchez et al. 2011 and Braidot et al. 2014).

This manipulation can, however, be achieved through several storage methods and modifications specific to different cultivars as noted by Bolin and Huxsoll (1991), which also involves the reduction of light intensity and exposure during storage (Martinez-Sanchez et al. 2011). Investigations on predictions of spinach quality based on pre and post-harvest conditions found that respiration rates during storage (post-harvest) were higher for field grown spinach (19.5-9.5 µl CO_2/g·h) compared to hydroponically cultivated spinach (13-8.5 µl CO_2/g·h) which significantly reduced the shelf life (Gutiérrez-Rodríguez et al. 2012). Therefore, the versatility of hydroponic systems on manipulation of crop growth and development variables allows for a crop production system configurable for shelf life enhancement.

Many researchers (Sanz et al. 2008; Ayala et al. 2009; Manzocco et al. 2011; Zhan et al. 2012) have found conflicting results on post-harvest storage conditions for leafy vegetables. Despite this, it is necessary to note that proper manipulation and management of plant growth and development variables can be of significance in enhancing shelf life quality, since they are responsible for plant physiochemical and morpho-anatomical growth and development which could be regarded as key indicators for either increased or decreased shelf life (El-Ramady et al. 2015). Therefore, grasping the significance of good pre-harvest crop production practices and their implications on the shelf life of crop produce creates awareness on how to control these variables to achieve the desired shelf life for meeting market demands and standards.

2.5 Nutrient solution management of soilless systems

Nutrient solutions for soilless systems are made up of an aqueous solutions containing mainly inorganic ions from soluble salts of essential elements, although some organic compounds such as iron chelates may be present (Steiner 1968). An essential element has a clear physiological role and its absence prevents the completion of the plant's life cycle (Taiz and Zeiger 1998). Currently 17 elements are considered essential for most plants. These are carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, iron, copper, zinc, manganese, molybdenum, boron, chlorine and nickel (Salisbury and Ross 1994). With the exception of carbon (C) and oxygen (O), which are supplied from the atmosphere, the essential elements are obtained from the soil. Other elements such as sodium, silicon, vanadium, selenium, cobalt, aluminium and iodine among others, are considered beneficial because some of them can stimulate the growth, or can compensate the toxic effects of other elements, or may replace essential nutrients in a less specific role (Trejo-Téllez et al. 2007). Table 3 depicts the most basic nutrient solutions for common hydroponically grown crops according to Deckers (2002) based on Steiner's mutual ionic relationships. Hydroponic solutions which are mainly composed of nitrogen, phosphorus, potassium, calcium, magnesium and sulphur are further supplemented with micronutrients to allow for optimum uptake of all essential elements (Table 3) and it is crucial to mention the need for a balanced relationship (ratio) of anions and cations (pH) and their concentrations (EC) as it allows for all essential elements to be easily accessible to the plant (Steiner 1961). Research by Sonneveld and Welles (2005) on the effect of cation concentrations in plant tissues demonstrated that EC values in the root environment increased with equal ratios of nutrients and interestingly found increased potassium content at reduced calcium uptake. The results further showed the relationship between the uptake of nutrient cations and their mutual ratios (pH) (Sonneveld and Voogt 2009). Therefore, it is crucial to understand that achieving desired crop yields requires proper nutrient solution compositions and management, bearing in mind that closed hydroponic systems will often allow the management aspect to be practiced easily, because it allows for less dozing of fertilizers since they are recycled for optimum uptake and efficient use by plants (Grewal et al. 2011).

Table 3: Basic nutrient solution formulas based on type of hydroponic system

Hydroponic system	MACRONUTRIENTS ($mmol.L^{-1}$)							EC ($mS.cm^{-1}$)	MICRONUTRIENTS ($mg.L^{-1}$)					
	NH_4	K	Ca	Mg	NO_3	H_2PO_4	SO_4		Fe	Mn	Zn	B	Cu	Mo
Drain to Waste														
Lettuce	0.7	5.5	5.8	1.0	10.0	1.0	2.0	1.30	1.00	0.55	0.25	0.30	0.05	0.05
Cucumber	1.0	5.5	7.5	2.5	13.0	1.0	2.5	1.65	0.85	0.55	0.30	0.30	0.05	0.05
Pepper	0.3	5.2	9.0	3.5	12.8	1.2	4.0	1.80	0.85	0.55	0.30	0.30	0.05	0.05
Tomatoes	1.0	7.0	8.5	3.5	12.5	1.5	6.0	2.00	0.85	0.55	0.30	0.30	0.05	0.05
Closed system														
Lettuce	0.6	3.9	3.8	0.6	7.0	0.8	1.1	0.89	1.00	0.55	0.25	0.30	0.05	0.05
Cucumber	0.8	4.5	5.3	1.8	9.6	1.0	1.8	1.24	0.85	0.55	0.30	0.30	0.05	0.05
Pepper	0.3	4.4	6.2	2.5	10.4	1.0	2.0	1.34	0.85	0.55	0.24	0.25	0.05	0.05
Tomatoes	0.8	4.8	4.3	2.2	8.3	1.2	2.6	1.21	0.85	0.55	0.24	0.20	0.05	0.05

Nutrient recycling and recirculation plays an important role because it does not only reduce fertilizer costs but is also less harmful to the environment. Hence it is considered is a sustainable crop production practice which allows for increased water use efficiency and nutrient uptake by plants. This is only achievable through soilless cultivation of crops and can be done using organic nutrient solution found in aquaponics where pond water is used as an alternative to inorganic nutrient solutions (Garland et al. 1993; Graber and Junge 2009; Libia et al. (2012). Libia et al. (2012) stated that soilless cultivation allows for a more precise control of root zone conditions that offers possibilities for increasing production and improving the quality of crops. Optimization of root zone areas for efficient nutrient solution uptake is governed by parameters such as temperature, pH, electrical conductivity, oxygen content among others, which can be manipulated with significant effect on plant growth and development (Sonneveld and Voogt 2001). Research has been done in this regard to evaluate the extent of which nutrient solutions conditions affect postharvest quality in hydroponically cultivated crops. Libia et al. (2012) explained the conditions indicating their significant effect on nutrient solutions and the uptake thereof. According to researchers, pH of the nutrient solution is a measure of alkalinity or acidity or the concentration of hydrogen ions in the solution with a range from 0 to 14, with 7 being neutrality of nutrient solution. Furthermore, pH is of significant importance because it is responsible for making nutrients easily accessible for the plants (Brechner 1996; Libia et al. 2012). Further conditioning of nutrient solution is electrical conductivity (EC), a measure of the dissolved salts in a nutrient solution in mS cm^{-1}

(Table 3). As nutrients are taken up by a plant, the EC level is lowered since there are fewer salts in the solution (Lykas et al. 2006). Early research studies, most notably Dr Cees Sonneveld in the 1980s demonstrated the influence of hydroponic nutrient solution strength (EC) on tomato post-harvest quality. He found that a rise in root environment solution strength from EC 2.6 to 3.5 mS cm^{-1} resulted in an increase in shelf life from 17.5 to 19.2 days, while the EC in fruit sap increased from 5.8 to 6.2 mS cm^{-1}. Additionally, the acids in the fruit sap increased from 75.0 to 84.0 mmol L^{-1} and the Brix ^{0}C of the fruit sap increased from 4.8 to 5.0%.

However, from the investigations it is necessary to mention that nutritional amendments in hydroponics is part of nutrient solution management meant to optimize nutrient solution conditions in the root zone to allow roots to take up nutrients easily (Napier and Combrink 2006). According to Bugbee (2004) recycling allows for efficient uptake of nutrients by the plant and is a sustainable practice with a significant effect on the post-harvest quality and therefore requires good management (Chenzhong et al. 2004). Poor nutrient solution management is noticed through observation of the crop produce for any nutritionally induced defects and by running a chemical analysis to determine which nutrient in particular has affected the postharvest qualities such as overall visual quality, nutritional quality and shelf life and to what extent.

2.5.1 Implications of nutrient solution management on the postharvest quality of lettuce

Nutrient solution management allows for accurate control of nutrient solution conditions that have a significant effect in increasing productivity and crop quality. Manipulation and management of these parameters such as pH, electrical conductivity (EC), temperature and oxygen content of the nutrient solution if not done properly and timely the benefits thereof become negated (Libia et al. 2012). Similarly, extremities in these parameters have catastrophic effects such as ion toxicity and imbalances resulting in nutrient deficiencies and disorders that affect the yield and overall post-harvest quality traits (Fallovo et al. 2009a). Commercializing soilless lettuce production systems for increased yield and crop quality therefore requires adequate supply of recommended levels of cation percentages of potassium (35%), calcium (45%) and magnesium (20%) and for anion percentages of nitrates (60%), phosphates (5%) and sulphates (35%) (Steiner 1961) have been proposed. Management of nutrient solutions to produce high-quality postharvest attributes is required and nutrient solution formulations largely depend on water analysis, crop type, type of nutrient delivery system and prevailing growing conditions, but follows the recommended Steiner solution (Hoque et al. 2010). Research by Fallovo et al. (2009) found that a high proportion of calcium in the nutrient solution increased the quality attributes in particular calcium, chlorophyll, glucose and fructose concentrations in lettuce. Furthermore, Chiloane (2012) noted that a calcium (Ca) cation ratio amendment regime had a significant effect on crop quality as it reduced chances of tipburn occurrence and therefore nutrient management has the potential to alleviate poor crop qualities at harvest. Nutrient solution temperature management also plays a significant role in enhancing crop quality. According to Adams and Ho (1993), root zone temperature also affected the uptake of Ca which increased at a range of 14 to 26°C while higher than that resulted in reduced uptake with a consequent effect on quality since tipburn is induced due to Ca deficiency. Furthermore, EC of nutrient solutions also affects overall visual quality particularly the colour of the lettuce crop. Chiloane (2012) found that lettuce plants grown with an EC of 3 $mS.cm^{-1}$ showed to have a dark green colour while plants grown with an EC of 2 and 4 $mS.cm^{-1}$ produced lettuce with normal green colour. Further researcher, found that adjustments of EC in regards to increasing nitrogen resulted in a significant reduction in leaf mineral content of B, Mg, Mn, and Zn which are key elements in plant leaf growth and development (Chiloane 2012).

2.5.2 Nutrient foliar applications

The integration of hydroponics and its acceptance as an independent crop production system has resulted in further research and development driven towards optimization of techniques applied in the skill of manipulation of plant growth variables to enhance nutrient uptake and plant use efficiency (Du Plooy et al. 2012). Nutrient foliar applications allows the administering of nutrients via the leaf surface through spraying of a fine mist of a specific nutrient solution and has resulted in improved resistance to pests, diseases, drought and other stresses on plants (Bacchus 2010). Further research has shown improved nutrient uptake from plant leaves and was been developed mainly on the basis of visual foliar symptoms or plant tissue tests. (Fageria et al. 2009).Chiloane (2012) investigated the effectiveness of Ca foliar sprays in reducing the incidence of tipburn occurrence, but was limited by cultivar type due to their morphological leaf structures. Furthermore, nutrient foliar effects were noted by Woolfolk et al. (2002) as they recorded an increase in grain nitrogen and protein in wheat after late application of nitrogen foliar spray. Therefore, to a greater extent, foliar applications are applied to remedy single nutrient deficiencies or as supplements which aid in achieving the desired yield and crop quality. Since it is applicable to different cropping systems, this technique has been well researched and developed (Roosta and Hamidpour 2011). Furthermore, Roosta and Hamidpour (2011) found that the application of a foliar spray of K, Mg, Fe, Mn, and B in aquaponics resulted in an increase in plant growth whilst in the hydroponics, Fe and B foliar applications produced positive effects on plant growth while foliar application of K, Mg and Zn increased fruit number and yield.

It is pivotal to note that most occurring post-harvest disorders are highly related to nutrient deficiencies which are the adverse effects of poor nutrient solution management but can be remedied by nutrient foliar applications (López-Millán et al. 2009). Therefore the adaptation of nutrient foliar applications to remedy such issues is of greater significance across all crop production platforms as it is easily applied, effective and economical and a sustainable solution. Foliar applications are made up of different formulations and combinations to serve different objectives such as improving crop quality. Moor et al. (2006), observed that from single and mixed nutrient foliar solution formulations, application largely depended on the severity of the nutrient deficiencies and through leaf chemical analysis..

2.6 Implications of light quality in controlled environments

There are many environmental factors affecting the growth and development of plants amongst which lighting conditions is one (Ohashi-Kaneko et al. 2007). Light intensity also has a strong influence growth, yield and on post-harvest quality. Light quality in crop production has to be understood as plants can only use a specific type of wavelength (Li et al. 2014). Light spectrum is made up of visual colours from shortest to longest wavelength which are violet, blue, green, yellow, orange, and red with white light being a mixture of the colours of the visible spectrum. Further research has shown that plants respond differently to blue, green, yellow and red colours at different plant growth stages (Ohashi-Kaneko et al. 2007; Fu et al. 2012b). In this regard, the significant effect of light quality on crop growth and development has to a larger extent been investigated. Eskins et al. (1995) found that light quality signals received in the early growth environment has a latent effect on subsequent plant development, which illustrates the effect of light quality management. Research by Mortensen and Strømme (1987) on the effects of light quality on some greenhouse crops found that different light qualities such as blue, green, yellow and red had an influence on plant morphogenesis when compared to natural light. Furthermore, their results revealed that green and yellow lights resulted in increased leaf area for lettuce when compared to white light and in tomatoes plant height and total leaf area were significantly higher when compared to natural light. The results were supported by Ohashi-Kaneko et al. (2007) who noted that light quality can have a profound effect on plant growth, development and physiology and in their study they found that cultivation under blue or a combination of blue and red light can produce high quality leaf lettuce with rich L-ascorbic content and decreased nitrates.

The ability to manipulate light quality for optimum plant growth and development has resulted in the further understanding of the role of light quality. Research on light quality has been conducted to provide the optimum wavelength for efficient photosynthesis in plants (Shimizu et al. 2011). Hydroponic plant production systems with supplemental lighting have numerous potential benefits such as, shorter production periods, high quality transplants and marginal use of resources (Kozai 2013). Natural light intensity has been a huge limiting factor in greenhouse production in other areas around the globe characterized by a short photoperiod according to Dorais and Gosselin (2002) and its physiological influence has been well studied (Kozai 1977). Fu et al. (2012) recommends a range of 400-600 μmol m^{-2} s^{-1} light intensity for production of certain types of lettuce, and an intensity of 400 μmol m^{-2} s^{-1} can be an optimal value of supplementary light for winter greenhouse production of certain types of lettuce in higher latitudes, while light intensity of 600 μmol m^{-2} s^{-1} can be an optimal value of shading light for late spring and early autumn production of certain types of lettuce in lower latitudes. Light has been known to be fundamental in plant growth and development (Gaudreau et al. 1994).

Furthermore Dorais and Gosselin (2002) stated that the use of high energy lighting conditions increased productivity in controlled greenhouse environments. Gaudreau et al. (1994) further noted a significant increase in biomass where supplemental lighting was introduced. The ability to regulate light intensity in soilless controlled environments has furthered the understanding on the relationship of plant growth in regards to chlorophyll content which is a significant indicator for postharvest OVQ. Soilless cultivation is mainly practiced under a form of cladding, be it glass or plastic, and these materials affect the type and amount of light being received and utilized by the plants. Therefore, it is necessary to understand the impact of light intensity management on crop production and quality thereof.

2.6.1 Implications of light intensity on the growth and postharvest quality of lettuce

Previous studies have shown that increased light intensity promoted lettuce growth (Li and Kubota 2009) and that the growth promoting effect works within an optimal light intensity range of 15-17 μmol m^{-2} day^{-1} if vertical airflow fans are used. Values higher than this can result in the occurrence of leaf tipburn, a physiological disorder from calcium deficiency that can be triggered under high light (Mattson 2010). In order to maximize the economic benefit of obtaining higher yield and quality, research has shown that optimization of light intensity can be of significance at post-harvest. The overall visual appearance parameter of lettuce which to a larger extent is the green colour is also affected by light intensity during crop production and to be more specific the chlorophyll content index. Researchers have reported that a decrease in chlorophyll content observed in the external leaves of lettuce strongly correlated with the decrease in OVQ (Agüero et al. 2008). The use of a chlorophyll index to measure the green colour of lettuce has therefore been a method/ technique applied over several research and has produced compelling results (Caldwell and Britz 2006).

Fu et al. (2012) investigated the effects of different light intensities on chlorophyll fluorescence characteristics in lettuce. Based on their results found that extremely strong light resulted in decreased chlorophyll content and furthermore confirmed the extended effect on different plant growth, development and other post-harvest parameters such as leaf area, leaf number and appearance which were higher under white light treatments. Furthermore, Fu et al. (2012) observed significant differences in yield among the 600, 100, 200, and 800 μmol m^{-2} s^{-1} light treatments. It is clear from their study that the implications of different light intensities are wide spread and inter linked with the crop life cycle. Further research has seen the effect of light intensity and photoperiod in inducing defects in crops which reduces the post-harvest quality of the crop as found by Gaudreau et al. (1994) where lettuce exposed to 100 μmol m^{-2} s^{-1} with a 24–16 hour photoperiod had severe tipburn occurrences affecting overall visual quality and marketability. Most research has shown the effect of different light quality and its significant effect on specific plant physio-morphological attributes and has further revealed the adverse effects on post-harvest quality. Therefore the necessity to optimize light quality and photo period is fundamental in enhancing post-harvest attributes and management in this regard requires meticulous execution.

2.7 Conclusions

The ability to manipulate plant growth variables, regulate use and efficiency by crops in hydroponic systems has been surgically analysed by researchers and is a step closer to achieving the desired outcome in crop production without the limitations and constraints of agro-ecological zoning. Substantial research has been carried out in order to develop the techniques applied in controlling these plant growth variables, but not to the same extent their adverse effects on the post-harvest quality. Not only should research focus on developing economic and sustainable means of hydroponic crop cultivation concentrating on the benefits of the hydroponic crop production system but should focus more on post-harvest quality aspects of crops from these systems so as to allow crop producers to be confident in the system especially in developing countries like South Africa. Therefore the objective of the study was to assess the effect of hydroponic management namely, nutrient solutions and light intensity and their adverse effects on post-harvest quality of cos and iceberg lettuce. These will be further explained or investigated in Chapter 3 which will focus on light intensity management and Chapter 4 which will focus on nutrient solution management through application of different calcium cation ratios whilst Chapter 5 will serve as a short investigation on the extent of nutrient foliar application on post-harvest quality.

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Chapter 3

Different light intensities (PAR) and the effect(s) on post-harvest quality in hydroponic production of iceberg and cos lettuce

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Abstract

One of the finer nuances of hydroponic systems is the ability to manipulate light variables for enhancing crop growth and quality attributes. In this study, the effect of different light intensities on post-harvest quality of lettuce (*Lactuca sativa*) types, iceberg (Commander) and cos lettuce (Triple Play) was investigated. The trial was conducted for 31 days from transplanting, in a glasshouse with average day and night temperatures of 20°C and 15°C. The trial was repeated for two consecutive seasons. Plants were completely randomised (CRD) and exposed to three different light intensities; control of 450 µmol m^{-2} s^{-1} (19.44 mol m^{-2} d^{-1}), 60% of control at 270 µmol m^{-2} s^{-1} (11.66 mol m^{-2} d^{-1}), 40% of control at 180 µmol m^{-2} s^{-1} (7.78 mol m^{-2} d^{-1}). Plants were grown using a nutrient solution with an EC of 1.30 mS cm^{-1} in a drain to waste system. The study showed that different light intensity treatments had an effect on the yield and post-harvest visual appearance, with decreasing light levels from 19.44 to 11.66 mol m^{-2} d^{-1} between the two types of lettuce. Differences in yield and colour were also significant with cos lettuce outperforming iceberg. Colour, a quality parameter was measured as chlorophyll content index (CCI) with cos lettuce having a higher average chlorophyll content index of 8.0 over iceberg with a mean of 6.1. Overall, visual appearance based on plant height (mm), indicated that cos lettuce plant height increased with 60% and 40% shading. Texture analysis (nm) was measured using Instron texture analyser in nm and a significant interaction was observed for this parameter with cos lettuce generally outperforming iceberg. Light quality manipulation effect on some post-harvest attributes of lettuce was observed indicating the ability to produce desired crop quality attributes in a hydroponic system.

Key words: chlorophyll content index (CCI), cultivar, daily light integral, lettuce, postharvest

3.1 Introduction

Since the introduction of hydroponic farming technology on the agricultural scene of South Africa, scepticism resulted in its slow incorporation and use by farmers. This was largely due to lack of understanding of the versatility of the system and the perceived adverse effects thereof apart from its known yield and increased production benefits (Du Plooy et al. 2012). However, over time it has become a widely used, promising and lucrative enterprise. As retailers of vegetables are starting to focus more on quality over quantity, hydroponic farming is again placed in the spotlight due to the abilities to manipulate plant growth and development variables for specific quality oriented results. In South Africa, lettuce production is practiced in greenhouses to protect against the strong UV radiation, to increase the humidity around plants, and to manipulate to some extent the extreme minimum and maximum temperatures that can occur in one single day. Most greenhouses in South Africa are cladded with polyethylene sheeting or shade netting.

According to Gaudreau et al. (1994) light is regarded as a primary factor regulating plant growth and development as it affects almost all plant functions. Crop quality and yield largely depend on light quality, quantity and light photoperiod which to a great extent work coherently (Mattson 2010). Light quantity, according to Danesi et al. (2004) is the total amount of light supplied to the plant, which is then used for photosynthesis. Up to a point the higher the light quantity the more energy a plant can sequester through photosynthesis. Daily light integral (DLI) tells us how much plant usable light, expressed as photosynthetic active radiation (PAR), the crop received inside the greenhouse during a 24 hour period (Dorais and Gosselin 2002). This is very important as it does not only affect growth and development but yield and quality. Research has found optimum PAR for hydroponic lettuce production to be around 15-17 mol m^{-2} day^{-1}. Research has shown that high light levels can possibly cause leaf tipburn, a physiological disorder resulting from calcium (Ca) deficiency (Torres and Lopez 2010). Some of the primary reasons why light levels together with temperature, irrigation, and photoperiod are manipulated in greenhouses are to minimize crop stress and optimize photosynthesis for optimum crop growth and development. Understanding the effect of light intensity on crop growth and development has aided in controlling hydroponic crop management across the globe. Researchers like Fu et al. (2012) recommended a range of 400–600 μmol m^{-2} s^{-1} as light intensity for production of certain types of lettuce. A light intensity of 400 μmol m^{-2} s^{-1} can be an optimal value of supplementary light for winter greenhouse production of certain types of lettuce in higher latitudes, while light intensity of 600 μmol m^{-2} s^{-1} can be an optimal value of shading light for late spring and early autumn production of certain types of lettuce in lower latitudes.

Lettuce has become a highly desired ready to eat leafy vegetable with its marketability largely dependent on its visual quality traits. It is important, therefore, to produce lettuce with desired post-harvest traits such as extended shelf life and overall visual quality (Scofield 1999). Since the leaf is the highly desired part of the lettuce crop, appearance and texture are the primary drivers for consumer acceptability (Mou 2008). Research has shown light quality to be a significant enhancer which could result in a decrease in those leaf quality traits if not optimized accordingly (Fu et al. 2012). Furthermore, leaf visual quality parameters largely affected by light quality are shape, form and colour. The ability to produce desired post-harvest attributes is therefore governed by the ability to provide specific light requirements during lettuce growth and development. Although several studies have recommended optimum light intensity levels for lettuce production based on supplemental lighting, it is necessary to note that little is known with regards to the effects of shade nets and light intensity on post-harvest quality, necessitating research in this regard. Therefore the objective of the study was to assess the extent of light intensity manipulation on post-harvest quality of commonly used lettuce cultivars in South Africa.

3.2 Materials and Methods

3.2.1 Seedlings

Eight to twelve day old lettuce (*Lactuca sativa*) seedlings of cos and iceberg types were supplied by Radical Seedlings located in Klapmuts, Stellenbosch, on 10 February 2016. The seedlings were propagated in seedling trays and before transplanting, a careful selection of viable, healthy, uniformly germinated and developed seedlings was made to ensure that all seedlings survived transplanting and had uniform growth.

3.2.2 Preparation of greenhouse and light levels

The experiment was conducted in a ventilated glasshouse at the Department of Agronomy at Stellenbosch University, Western Cape, South Africa, at day and night temperature ranges of 25°C and 15°C respectively and an optimal relative humidity (RH) range of 60% to 95% (Figure 3.1). A total of 42, 5 litre black potting bags were used in this experiment with 21 bags for each lettuce type. Bags were filled with coco peat that had been soaked to allow for expansion and better water holding capacity. The bags were perforated 5 mm from the bottom to allow excess water to drain. These bags were then placed a meter above ground on dripping trays to enable collection of the drainage water. Transplanting was done directly from seedling tray to potting bag and afterwards seedlings were shaded as per layout and design. Drip irrigation was used 3 times a day for 2 minutes per irrigation event in a drain to waste system at a rate of 2 litres per day per plant.

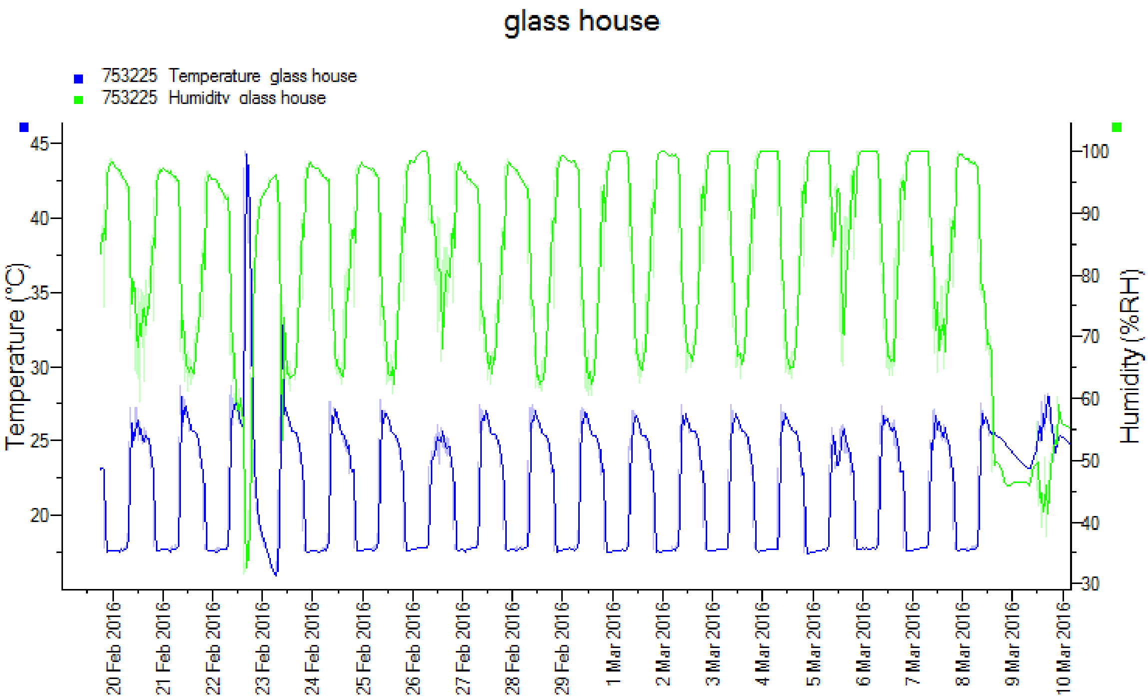


Figure 3.1: Temperature and relative humidity during the experiment

Three light levels were applied, the control at 450 µmol m^{-2} s^{-1} (19.44 mol m^{-2} d^{-1}), 60% of control at 270 µmol m^{-2} s^{-1} (11.66 mol m^{-2} d^{-1}) and 40% of control at 180 µmol m^{-2} s^{-1} (7.78 mol m^{-2} d^{-1}) which were manipulated through the use of shade nets, having calculated the control level using the AccuPAR, PAR/LAI Ceptometer, which was the natural daily light integral found in the glass house indicated as 100%.

3.2.3 Experimental layout

Treatments were made up of two types of lettuce types (cos, cultivar Triple Play and iceberg, cultivar Commander) exposed to the three PAR levels.

The total number of experimental units was 42, viz 21 for cos lettuce and 21 for iceberg lettuce respectively. The experiment was laid out as a completely randomised design (CRD) with seven replicates for each cultivar.

3.2.4 Measurements and analysis

Seedlings were considered viable with the emergence of the third leaf. Plant growth and development was constantly monitored on a visual basis and climatic variables measured daily at 10 second intervals with a Tiny Tag relative humidity and temperature data logger.

The chlorophyll content was measured by obtaining 3 leaves per sample, collected from different sections on the plant. A section of that leaf was placed under the chlorophyll meter to obtain the chlorophyll content index. The sum of all three readings per plant were then averaged to give the final plant chlorophyll content index, where *cci* is chlorophyll content and n is number of leaf samples (Rodriguez and Miller 2000).

$$\text{Average chlorophyll content, (AVE CCI)} = \frac{cci^1 + cci^2 + cci^3}{\mathrm{n}}$$

Plant height was measured using a tape measure as the distance (mm) from the top of the growth medium to the top of the plant canopy or height above ground (Heady 1957). Leaf texture was measured using the Instron texture analyser. An average texture reading was recorded from three sections of the leaf/sample namely: the bottom part of the leaf (petiole), the mid-section (mid rib) and the apex section. Samples were cut into 200 mm x 400 mm sections before being placed on the cutting bed, held in place while an automated blade was forced through the leaf samples at a speed of 200 m min^{-1}. The force required to cut through the leaf sections was measured and interpreted as follows:

- Where *nm* represented force and n represented the total number of cut section/leaf/plant (Scofield 1999; Manzocco et al. 2011).

  $$\text{Average texture (AVE TXT nm)} = \frac{nm^1 + nm^{2} + nm^{3}}{\mathrm{n}}$$

- Higher nm readings meant 'less crispy' and lower nm readings meant 'more crispy'.

Fresh weight(g) was measured upon harvest and dry weights (g) after oven drying for 2 days (Stefanelli et al. 2011).

3.2.4 Statistical analysis

The data was subjected to Analysis of Variance (ANOVA) using STATISTICA software version 13. The Fisher's least significant difference (LSD) (P = 0.05) was used for separation of means.

3.3 Results and discussion

The lettuce types differed significantly with regards to all parameters, while light intensity levels also had significant effect on measured parameters. Interactions between the light intensity treatments and lettuce types were only statistically significant for crispness and plant height parameters and for this reason the main effects (lettuce type and light intensity) will not be discussed for these parameters.

3.3.1 Yield Index (Fresh Weights)

No statistically significant interaction between the main effects (light intensity and lettuce type) was observed as shown in Table 3.1 ($P < 0.05$). Light intensity treatment did however have a significant effect on the fresh weights and differed significantly between the lettuce types (Table 3.1). A significant increase in fresh weight was observed as the light intensity increased from 40% of the control to 60% of the control and then to the control (full sunlight) and can be largely attributed to low light intensity which although stimulates stem elongation, reduces vegetative canopy development. At higher light levels, leaf growth and development will be stimulated due to expansion of leaf area index for maximum absorption of light hence the increase in yield (Gaudreau et al. 1994). In greenhouses, the light levels reaching plants is often reduced as a result of the type of plastic cladding (shading that is applied to reduce temperatures) or as a result of high planting densities. These results thus show that even for lettuce it is important to maintain high solar radiation levels. A significant difference in yield between lettuce types was also observed with cos lettuce having a higher yield compared to iceberg. This variation was largely as a result of the observed inability of the iceberg cultivar to head at lower LI treatments and also due to stem elongation (bolting). These results are supported by the findings of Furuyama et al. (2014) who also found malformed leaf shapes associated with low light intensity. In the case of the cos lettuce, due to its morphology of being an open broad leaved type, the decreased light intensity resulted in broader leaf development maximising area for light interception hence the significant differences between the two lettuce types on fresh weight. This was also observed by Son and Oh (2013) who reported a significantly higher leaf shape index which represented elongated shape leaf for lettuce cultivars that had been treated with 100% red led light intensity. Li and Kubota (2009) also observed that fresh weight together with leaf length, width and area significantly increased with supplemental lighting. This explains the effect of light intensity levels on different lettuce types and post-harvest variables including yield and visual appearance (Kang et al. 2013).

Table 3.1: The effect of light intensity treatments and lettuce type on plants' postharvest fresh weight (g). Means within the column followed by different letters are significantly different at $P<0.05$.

EFFECT	N	FRESH WEIGHT MEANS
LI CONTROL	28	258.00a
LI 60%	28	118.75b
LI 40%	28	72.25c
COS LETTUCE	42	203.82a
ICEBERG	42	95.50b

ANOVA	*F*-VALUE	Pr>*F*	Significance
Treatment	33.13	<0.0000	**
Lettuce type	31.21	<0.0000	**
Treatment*Lettuce type	3.10	0.0514	ns

** p<0.01; ns, not significant at p = 0.05

3.3.2 Chlorophyll Content

For chlorophyll content index no statistical significance was shown with regards to interactions between the main effects (light levels and lettuce type) and neither was it affected by the light intensity treatments (Table 3.2). The lettuce types did however statistically differ with regards to their chlorophyll content. As expected, cos lettuce had a significantly higher chlorophyll content with a mean index value of 8.0 CCI compared to iceberg with a significantly lower CCI mean of 6.2 as shown in Table 3.3. These significant differences observed between average CCI for cos and iceberg types could be associated with photomorphogenesis which in the case of iceberg resulted in malformed leaf structure which affected photosynthetic potential of the cultivar and resulted in subsequent reduced chlorophyll content production, whilst in the case of cos lettuce the opposite can be said to be true. However Johkan et al. (2012) reported conflicting results, which accredited chlorophyll content levels and photomorphogenesis to adverse effects of different light intensity levels. This was also noted by Caldwell and Britz (2006) who reported that supplemental UV-B (290-320 nm) radiation increased the chlorophyll concentration of green leaf lettuce. They further reported that cultivars responded differently to light intensities and that selection of specific leaf lettuce varieties for greenhouse production will influence postharvest parameters. This is in accordance with the findings of Ohashi-Kaneko et al. (2007) who reported significant differences between cultivars with regards to postharvest parameters and a strong correlation of cultivar with chlorophyll content and its effect on overall visual quality (Agüero et al. 2008). Further research has shown chlorophyll as a phytochemical that is highly influenced by cultivar and LI levels (Li and Kubota 2009).

Table 3.2 Postharvest chlorophyll content as affected by light intensity treatments and lettuce type. Means within the column followed by the same letter are not significantly different at P<0.05.

EFFECT	N	AVERAGE CCI MEANS
LI CONTROL	28	7.15a
LI 60%	28	7.31a
LI 40%	28	6.83a
COS LETTUCE	42	8.00a
ICEBERG	42	6.19b

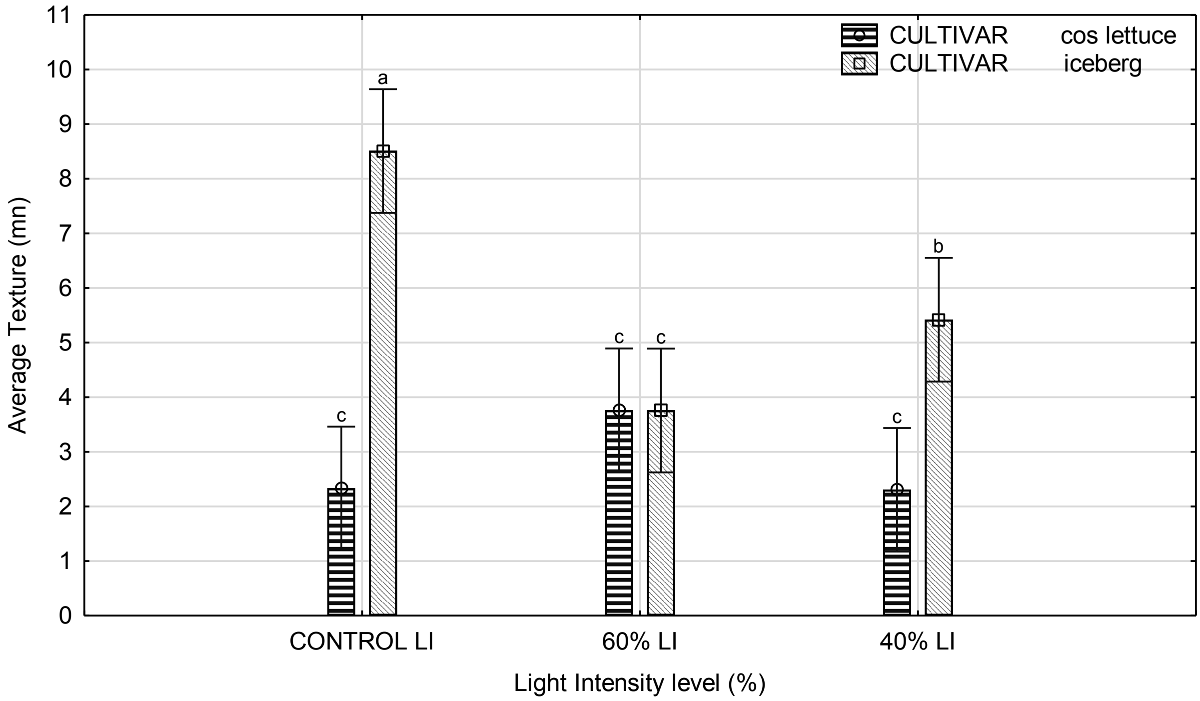
ANOVA	*F*-VALUE	Pr>*F*	Significance
Treatment	0.3872	0.6735	ns
Cultivar	16.098	0.0001	**
Treatment*cultivar	2.7111	0.0728	ns

*p<0.05, ns, not significant at p = 0.05

3.3.3 Texture Quality (Crispness)

The effect of light intensity levels as well as the lettuce type interactions on the texture of cos and iceberg cultivars is shown in Figure 3.2 with P<0.05. Generally, LI levels had an effect on the texture of the cos and iceberg lettuce with a significantly high crispness quality for cos lettuce since low force was required to cut through it compared to iceberg lettuce with higher force requirements. The variation between textures for both types can possibly be associated with how LI levels that influence the uptake of essential texture stimulating nutrients like calcium, boron and nitrogen, the moisture and phytochemical content, coupled with the interaction of cultivar or type (Colonna 2016). However, significant differences were observed for iceberg under all treatments with a crispier quality achieved when plants received only 60% of the control LI. This was also reported by Colonna et al. (2016) that when leafy vegetables were harvested at low as opposed to high PAR, the leaf content was higher in DM, protein, K, Ca and Mg. To a larger extent, the high crispness at low light can therefore be attributed to high moisture and chemical content in the leaves as observed at 60% light intensity where both lettuce types had the same texture quality.

Furthermore, as noted and observed by Colonna et al. (2016), low light levels in this study also resulted in increased texture for both cultivars at 40% and 60%. This could possibly have been due to transpiration which was triggered by light promoting uptake of calcium which improves and maintains plant cell walls. Other researchers have correlated phytochemicals of different cultivars to texture quality and influence of light intensity. For example Li and Kubota (2009) reported that after 12 days of light quality treatment (22 days after germination), phytochemical concentrations were significantly affected by light treatments with increased concentrations of specific phytochemical anthocyanin, carotenoids and phenolics whilst a decrease in anthocyanin, carotenoids and chlorophyll concentration by 40%, 11% and 14%, respectively was found under different light qualities. This shows that chemical concentration footprints in the plant cells will result in increased or decreased volume which contributes to leaf firmness and crispness. It is necessary to mention that light intensity influences metabolism which produces chemical by-products that contribute to the firmness of the leaf improving its texture. The results obtained have shown the effects of hydroponic light management on leaf vegetable texture.



ANOVA	*F*-VALUE	Pr>*F*	Significance
Treatment*cultivar	15.3139	<0.0000	**

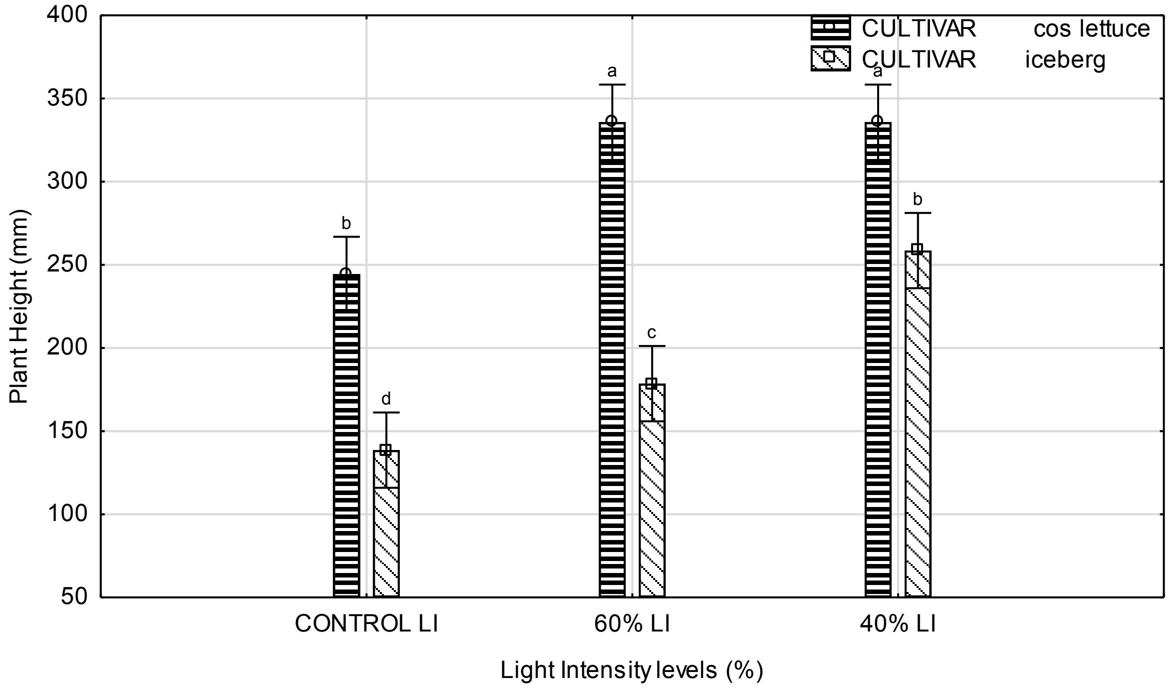
** *p*<0.01; ns, not significant at *p* = 0.0

Figure 3.2: Interaction between lettuce type and light intensity treatment on postharvest texture (nm) for cos and iceberg lettuce. Treatment combinations with different letter symbols differ significantly (*P* <0.05)

3.3.4 Plant Height

The effect of light intensity levels, the difference between lettuce types and the interaction effects on plant height for both cos and iceberg types is shown in Figure 3.3 with $P<0.05$. Light intensity levels had a significant effect on plant height for both lettuce types but to a greater extent for iceberg lettuce at 40% LI which measured at the same height with cos lettuce at control LI. The interactions were caused by 60% LI and 40% LI being the same for cos lettuce, but the response was different for iceberg caused by physiological changes, a consequent effect of photomorphogenesis where iceberg instead of forming heads developed long stems and small rugged shaped leaves while cos lettuce increased leaf area in an effort to better intercept light. This is in accordance with the findings of Kang et al. (2013) who reported that high light intensity of 290 µmol m^{-2} s^{-1} PPFD with a shorter photoperiod of 6/2 (light/dark) resulted in good plant growth and development of lettuce whilst a combination of 290-9/3 (light intensity-photoperiod) showed the highest plant height and fresh shoot weight. This showed the essentiality of optimization of LI and photoperiod in order to achieve desired post-harvest enhancement. Further physiological reactions to light intensity levels can be observed in Figure 3.3 where a gradual increase in plant height was observed for both cultivars from the control to 40% LI. Vast research has shown this trend or behaviour in plant response to either increasing or decreasing light levels (Glenn et al. 1984; Mortensen and Strømme 1987). In the case of cos lettuce, significant differences were observed at control LI and 60% LI although no significant differences were observed between 60% LI and 40% LI. The inability for further height increase from 60% to 40% LI for cos lettuce could be the result of increased leaf expansion in comparison to stem length, a possible compensation whereby outer leaves become highly invested in intercepting and absorbing light for photosynthesis hindering possible stem elongation since less light is intercepted by the stem hence an overall effect of lettuce type (Raikhel 2003).

Figure 3.3: Interaction between cultivar and treatment on postharvest plant height (mm) for cos and iceberg lettuce. Treatment combinations with different letter symbols differ significantly (*P* <0.05)



ANOVA	*F*-VALUE	Pr>*F*	Significance
Treatment*cultivar	6.601	0.0036	**

** p<0.01; ns, not significant at p = 0.05

3.5 Conclusions

In general, the study showed that greenhouse light intensity levels had a significant effect on yield and crispness and plant height for the two lettuce types tested. However, it is interesting to note that the aforementioned have a strong correlation to crop type as observed from the results where cos lettuce developed relatively long leaves at low light intensity, a desired trait for the cultivar whilst for iceberg it resulted in malformation of heads, an undesirable trait. Furthermore, although light intensity effects were observed it is of significance to note and understand that the response to the LI treatments stems from phytochemical and photomorphogenesis changes and the genetic make-up of the different lettuce types.

However, the study provided further evidence that light intensity in hydroponic systems compared to light intensity in the open field can be controlled by use of shade nets or plastics to filter out excess light characteristic of South African climates to achieve desired post-harvest traits. Furthermore, it has revealed that optimum light intensity in a greenhouse is ideal for lettuce production with a significant effect on overall visual quality and that greenhouse lettuce farmers can produce lettuce under specific light condition for a specific effect on yield, texture, colour and plant height This ability gives the system a more comparative advantage over producing lettuce in an open field.

From the study we can conclude that not only optimal light intensity levels are necessary to achieve desired effects but the right cultivar for the right LI level also has to be selected with genetic characteristics that can be manipulated for desired effect. Furthermore, that supplemental lighting or shading is a necessary tool for optimization of light intensity levels which is achievable in a greenhouse crop production system. However, we recommend further research to be carried out to identify a specific light intensity level ideal for a specific cultivar type and the effect of the interaction on chemical footprints within the plant cells to determine the extent to which that contributes to either enhancing or reducing quality.

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Chapter 4

Nutrient solution composition (Ca^{2+} cation ratios) and the effect(s) on yield and nutrient uptake in hydroponic production of Commander and Triple Play

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Abstract

Hydroponic fertilization fundamentals are undercut by lack of understanding the significance of a well-conditioned and managed nutrient formulation which is pivotal for increased productivity and crop quality. In this study, the effect of three different nutrient solution cation concentration treatments of 45% Ca^{2+} cation (S1), 20% Ca^{2+} cation (S2) and 60% Ca^{2+} cation (S3) all at an EC of 1.30 mS cm^{-1} on yield and leaf nutrient content was evaluated for two lettuce (*Lactuca sativa*) types, iceberg (cv Commander) and cos (cv Triple Play). Yield variable was unaffected by the different Ca^{2+} cation concentrations but cultivar had a significant effect on yield with cos lettuce having a mean fresh weight of 547 g and iceberg yielding 319 g although not statistically different. Leaf mineral content was affected by both cultivar and treatment interaction with calcium (Ca^{2+}), potassium (K^+)and boron (B) showing significant increases and decreases in that regard. A full chemical analysis for micro- and macro elements indicated that key nutrients responsible for crop quality (calcium, boron and potassium) were significantly affected by the treatments. Calcium cation concentration showed no marked effect when either increased or decreased on magnesium uptake and leaf content in the leaves. Nutrient solution management particularly cation concentrations can affect nutrient uptake and composition having an adverse effect on post-harvest quality of different types of lettuce.

Key words: *boron, calcium, cation concentration, nutrients, mineral composition*

4.1 Introduction

The increase in hydroponic crop production over the years and advances in market and consumer needs resulted in numerous research studies addressing the improvement of the production techniques. Hydroponic production has been shown to have a high efficiency rating in regards to water, land and energy use (Barbosa et al. 2015). It is also efficient regarding fertilizer use, climate control and pest management (Libia et al. 2012). Application of this crop production method has increased crop yields and crop quality without the seasonal limitations and other problems associated with open field cultivation (Savvas 2003). Hydroponic crop production has been underlined with the cultivation of crops in a water base solution but over the years the cultivation has also included the use of inert, artificial mediums for mechanical support (Jensen and Collins 1985). Therefore the key element supporting the system is a water based nutrient solution and it is pivotal that the composition, conditions and supply of this solution are meticulously monitored and managed to satisfy plant nutrient requirements for optimum growth and development (Libia et al. 2012). Plant productivity is closely related to the uptake of each nutrient, thus an important feature of nutrient solutions is that they must contain the ions in solution and in chemical forms that can easily be absorbed by plants (Marschner 2012). Management of the nutrient solution entails the balancing of cations and anions within the plant root zone which over the years has been developed to suit different crop needs and delivery systems (Sonneveld and Voogt 2009; Libia et al. 2012).

Lettuce production has seen a boost over the years largely due to its cultivation in hydroponic systems, which have been optimised production systems (Brechner 1996; Both 2003; Ioslovich 2009). Chiloane (2012) stated that nutrient solutions are pragmatic solutions of controlling and enhancing not only yield but nutritional quality of hydroponically cultivated crops. Furthermore, in his study he found that plant growth was less affected by nutrient concentration than by growing season but that quality was influenced by nutrient concentrations during the summer to autumn seasons, where increasing nutrient concentration resulted in increased chlorophyll content of the leaves. This shows the importance of understanding the management of plant growth and development variables in controlled environments such as manipulating optimum seasonal conditions and nutrient solutions that will stimulate growth and development and to a larger extent shows how versatile hydroponic systems are on influencing crop quality and yield (Agüero et al. 2008). There is already an established agricultural norm that hydroponic cultivation produces good quality crops (Grewal et al. 2011; Fan et al. 2012). Nutrient uptake by hydroponically grown crops depends on the availability of nutrients for uptake. Since many variables are controlled that affect crop growth and development it is crucial to develop a balanced nutrient solution for plant requirements (Barker and Pilbeam 2007). According to Steiner (1961) the composition and concentration of the nutrient solutions are dependent on culture system, crop development stage, and environmental conditions. Therefore the selection and the concentration of a nutrient solution should be such that water and total ions are absorbed by the plant in the same proportion to those present in the solution. Because of vast research in regards to nutrient uptake for soilless cultivation systems, its application in lettuce production has aided in increasing yields. It can furthermore be used to predict the effects of different concentrations in regards to crop quality aspects aiding the South African hydroponic lettuce growers to control post-harvest quality parameters during the pre-harvest crop production period.

However, lettuce grown hydroponically is more susceptible to nutrient induced diseases and disorders during production and at post-harvest of which the most common disorder is tipburn (Collier and Tibbitts 1982; Hoque et al. 2010). The occurrence of tipburn has been largely attributed to an imbalance in the nutrient solution and particularly calcium (Ca) which is responsible for cell wall strength (Huett 1994). However, researchers have also identified other interacting factors contributing to tipburn occurrences in hydroponic lettuce such as temperature, humidity and light (Collier and Tibbitts 1982b; Gaudreau et al. 1994; Chiloane 2012). The cause and effect of tipburn has become important as it has a ripple effect from farmer to retailer to customer. Although Saure (1998) notes that tipburn is more stress related than a Ca related disorder, this is still highly debateable since many researchers still believe it to be mainly a Ca related disorder (Huett 1994; Carassay et al. 2012). It is, therefore, necessary to investigate the effect of cation concentrations in relation to Ca ratios on plant yield and nutrient content. The objective of the study was to assess the impact of cation concentrations of nutrient solutions in lettuce grown hydroponically and their effects on post-harvest parameter yield and nutritive values.

4.2 Material and Methods

4.2.1 Experimental site and trial set-up

The experiment was conducted in a ventilated plastic tunnel at the Department of Agronomy at Stellenbosch University, Western Cape, South Africa, at day and night temperatures of 20°C and 15°C respectively and an optimal relative humidity (RH) range of 60% to 90%. Eight to twelve day old cos and iceberg lettuce seedlings (cos lettuce cultivar Triple Play and iceberg lettuce cultivar Commander) were supplied by Radical Seedlings located out of Stellenbosch. Before transplanting of both cultivars, healthy and uniformly germinated and developed seedlings were selected to ensure that all seedlings survived the transplanting and had uniform growth.

4.2.2 Treatments

Treatments were made up of two types of lettuce (cos lettuce cultivar Triple Play and iceberg lettuce cultivar Commander) exposed to three nutrient solutions. The solutions contained different cation ratios (Tables 4.1 and 4.2); a control solution where the Ca^{2+} made-up 45% of total cations (S1), a low Ca^{+2} treatment where the Ca^{2+} made-up 20% of the cations (S2) and high Ca^{2+} treatment where the Ca^{2+} made-up 60% of the cations (S3). All solutions had an EC of 1.30 mS cm^{-1} made-up in 1500 l water tanks respectively. Nutrient solutions were applied via drip irrigation in a drain to waste system. Sources from different fertilizers are shown in Table 4.1. The total number of experimental units was 42, viz 21 for cos and 21 for iceberg respectively. A total of 42, 5 litre black potting bags were used in this experiment with 21 bags for each cultivar. The potting bags were perforated 5 mm from the bottom to allow excess water to drain. Bags were placed a meter above ground on dripping trays to collect the drainage water. The bags were filled in with an inert pre-treated coir substrate that had been soaked to allow it to expand and to have better water holding capacity (WHC). Transplanting was done directly from seedling tray to potting bag and after irrigation, treatments were placed as per layout and design. Drip irrigation was used 3 times a day in the drain to waste system and at a rate of 2 litres/day/plant.

Table 4.1: Fertilizer concentrations used to compile the three nutrient solutions used for irrigating the lettuce plants. Each solution was made-up in 1500 l tanks at an EC of 1.30 mS cm^{-1}

Fertilizer source (g)	**Solution 1 (45% Ca)**	**Solution 2 (20% Ca)**	**Solution 3 (60% Ca)**
KNO_3	252.5	121.2	272.7
K_2SO_4	174	—	—
KH_2PO_4	136	136	136
NH_4NO_3	56	288	40
$CaNO_3$	580	210	580
$MgNO_3$	128	396.8	128
$MgSO_4$	—	246	—
$CaSO_4$	—	—	140
Omni spoor**	30	30	30

** Standard application 20 g/1000 l.

Table 4.2: Cation and anion percentages in the nutrient solutions used to fertigate two lettuce types during their growth cycle. The EC of all the solutions was 1.30 mS cm^{-1}

	Cations			Anions		
Nutrient solution	**Ca^{2+}**	**K^{+}**	**Mg^{2+}**	**NO_3^-**	**$H_2PO_4^-$**	**SO_4^{2-}**
Solution 1 (S1)	45	35	20	60	5	35
Solution 2 (S2)	20	57	23	60	5	35
Solution 3 (S3)	60	25	15	60	5	35

4.2.4 Measurements and analysis

Seedlings were considered viable with the emergence of the third leaf. Plant growth and development was constantly monitored on a visual basis observing any deficiencies or physiological disorders such as tipburn. A standard preventative pest and disease management program was followed. Climatic variables were measured daily at 10 second intervals with a Tiny Tag relative humidity and temperature data logger. At the final harvest, 30 days after planting, the samples were stripped of the outer leaves and roots removed for fresh weight measurements. Dry weights were recorded after oven drying for 2 days at $80^{O}C$. To assess the nutritional content, samples were dried, milled and sent to Bemlab for full chemical analysis of all the macro and micro elements.

4.2.5 Trial layout and statistical analysis

The experiment was laid out as a Complete Randomised Design (CRD) with seven replicates per treatment combination. The data was subjected to Analysis of Variance (ANOVA) using STATISTICA software version 13. The Fisher's least significant difference (LSD) (P = 0.05) test was used for separation of means.

4.3 Results and discussion

The cos and iceberg lettuce cultivars did not differ significantly with regards to fresh weights for all three treatments. However, treatment x cultivar interactions were statistically significant for cation concentrations for some key elements responsible for post-harvest quality. For this reason, main effects (cultivar and treatment) will not be discussed for those elements.

4.3.1 Yield index (fresh weight)

Fresh weight was unaffected by the Ca^{2+} cation concentrations, whilst there was not a statistically significant difference between the cultivars (Table 4.3). Similarly it was, observed that generally, leaf number, leaf area, leaf area index, fresh leaf mass, dry leaf mass and dry root mass did not significantly differ with increasing nutrient concentrations and therefore, yield was not influenced by nutrient concentrations (Chiloane 2012). In addition, Fallovo et al. (2009a) from their study also stated that marketable yield, shoot biomass and leaf area index were unaffected by nutrient solution composition. However, looking at the treatment and cultivar means there were marginal differences observed (Table 4.3). Treatment variation observed for mean fresh weight (FW) showed reduced yield for lettuce grown at 20% Ca^{2+} (S1) concentration and increasing the Ca^{2+} concentration from 45% (S2) to 60% (S3) did not significantly improve FW. The differences, however, in mean FW at 45% (S1) from 20% (S2) and 60% (S3) could be the result of Mg^{2+}: K^{+}: Ca^{2+} ratios (Table 4.2). Very high K fertilization causes reduced uptake of Mg^{2+} and Ca^{2+} because of K toxicity effect (McCauley et al. 2011). This was also observed by Tzortzakis (2009) that lettuce supplied with 10 mg of K_2SO_4 had reduced leaf fresh weight and leaf area.

It has long been acknowledged that while, cation and anion concentrations should be balanced but specific nutrient ratios should also be formulated for an effective and efficient uptake of all nutrients in their right quantities for optimum plant growth and development (Adams 1992; Taiz and Zeiger 2010) as well as to reduce the toxicity effects associated with high dosages of specific elements, like K^{+} (Yang et al. 2007). Cultivar differences were also observed, Triple Play had a higher FW mean of 548 g and DW mean of 17 g whilst Commander had a mean FW of 319 g and DW mean of 9.5 g (Table 4.3). This variation in the cultivar FW and DW is likely the result of different plant genetics particularly their physiochemical characteristics that influence plant and nutrient interaction (Barker and Pilbeam 2007; Wortman 2015) and also differing growth and development rates between cultivars (Mou 2009).

Table 4.3: Effect of cation concentration in the applied nutrient solution for Triple Play and Commander Lettuce cultivars on fresh weight yield of plants

ANOVA	*F*-value	Pr > *F*	Significance
Treatment	0.40577	0.6683	ns
Cultivar	2.34609	0.1308	ns
Cultivar*treatment	0.54327	0.5836	ns

ns, not significant at $p = 0.05$

EFFECT	N	Fresh Weight Means
Nutrient solution 1 (20%)	22	475.87a
Nutrient solution 2 (45%)	22	338.66b
Nutrient solution 3 (60%)	23	486.08a
Cos	36	547.74a
Iceberg	31	319.34b

Means within the column for each treatment effect followed by different letters are significantly different at $P < 0.05$.

Table 4.4: Effect of cation concentration in the applied nutrient solution for Triple Play and Commander Lettuce cultivars on dry weight of plants and overall moisture content

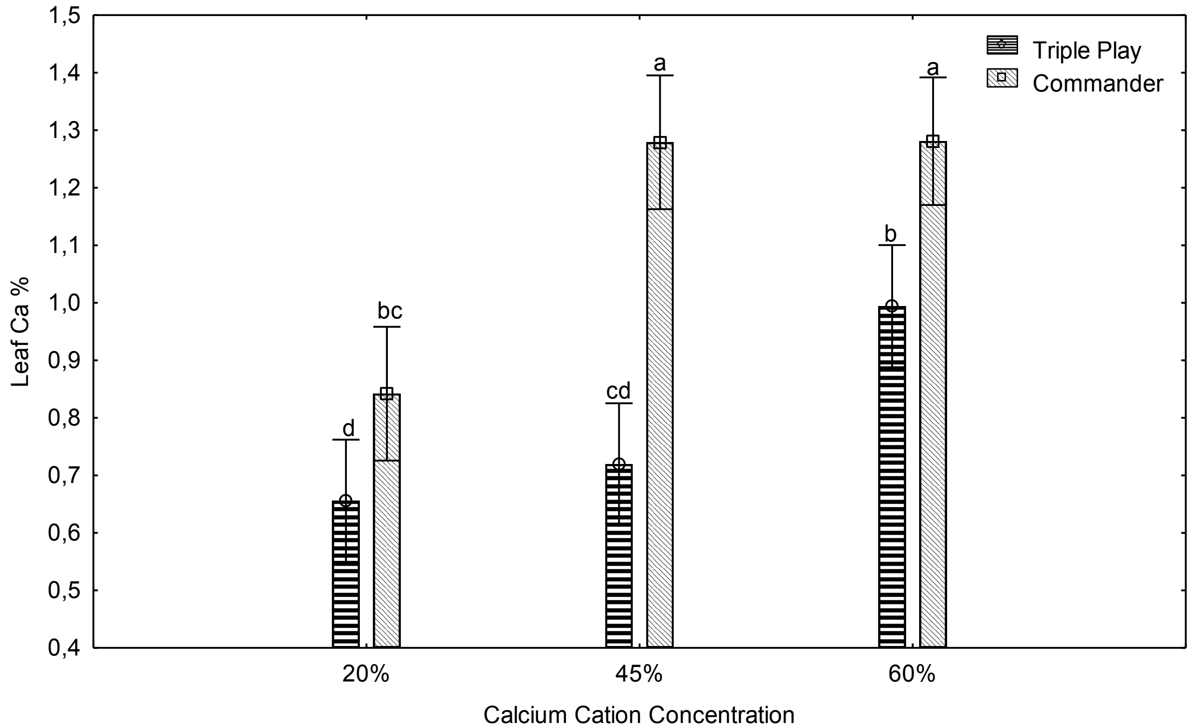
ANOVA	*F*-value	Pr > *F*	Significance
Treatment	0.8977	0.4129	ns
Cultivar	22.0549	0.000	**
Cultivar*treatment	0.3793	0.5836	ns

** $p < 0.01$; ns, not significant at $p = 0.05$.

EFFECT	N	Dry Weight Means
Nutrient solution 1 (45%)	22	14.42861a
Nutrient solution 2 (20%)	22	14.06028a
Nutrient solution 3 (60%)	23	11.89111a
Cos	36	17.42444a
Iceberg	31	9.49556b

4.3.2 Calcium content

Significant interaction was observed for treatment and cultivar in regards to calcium uptake by the plants (Figure 4.1). Commander (iceberg lettuce) had the highest Ca^{2+} content across all treatments with an increase from 20% Ca^{2+} to a constant at 45% and 60% Ca^{2+}. The increase in Ca^{2+} across all the treatments and between the cultivars is a clear indication that calcium absorption to a greater extent is influenced by both calcium cation concentration and lettuce type since calcium is a highly immobile nutrient, meaning that dosages will correlate to leaf Ca^{2+} content under the right conditions (McCauley et al. 2011). Regarding cultivar variation and leaf Ca^{2+} content, Commander significantly differed from Triple Play in leaf Ca^{2+} content. Interactions were observed with relatively higher Ca leaf content for iceberg at 45% and 60% LI for Commander whilst at the same levels Triple Play had significantly low Ca leaf content. This could have been the result of localised calcium deficiency in the leaf area for Triple Play since it is a broad open leaved cultivar which intercepts very high light and radiation resulting in potentially reduced Ca^{2+} leaf content (Chiloane 2012). Furthermore, another plausible explanation could be the elevated growth and development rates due to a potentially higher photosynthetic capacity compared to Commander causing reduced uptake of Ca^{2+}. This correlates with the high FW for Triple Play compared to Commander though grown under the same variables and time frame. Also different K^{+} toxicity tolerance levels between the two types of lettuce which results in selective uptake of nutrients can be a cause (Kim et al. 2008).



ANOVA	*F*-value	Pr > *F*	Significance
Cultivar*treatment	5.963	0.0043	**

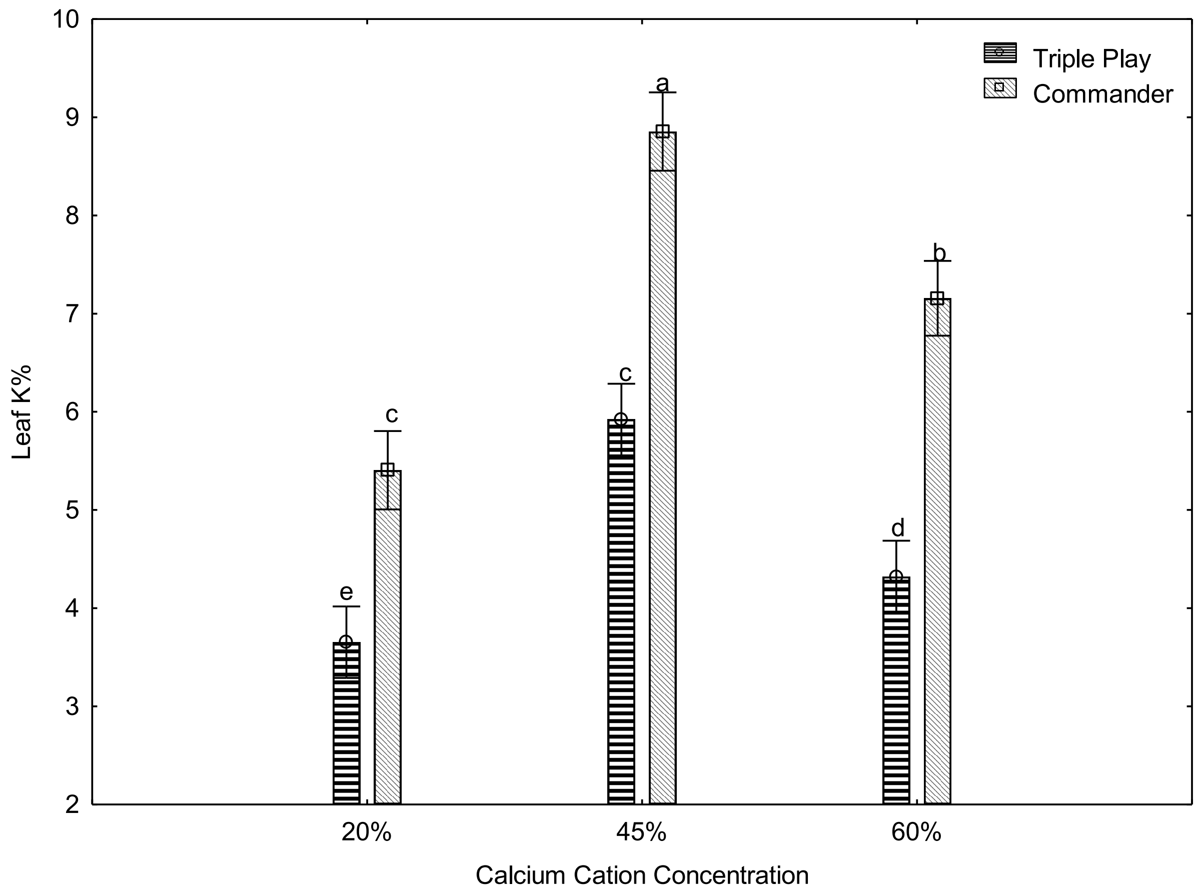
** $p < 0.01$; ns, not significant at $p = 0.05$

Figure 4.1: Calcium content of Triple Play (cos lettuce) and Commander (iceberg lettuce) cultivars as affected by different cation concentrations x cultivar interaction at harvest stage P < 0.05

4.3.3 Potassium content

Leaf K^+ content produced a two-way interaction between cultivar and Ca^{2+} cation concentration (Figure 4.2). K^+ content decreases were observed from the 45% (S1) control for both 20% (S2) and 60% (S3) Ca^{2+} cation treatments and cultivars. The results indicated to a greater extent treatment effects over cultivar effects and that increased or decreased Ca^{2+} concentrations had a significant effect on uptake and leaf K^+ content. You need to say again what the interactions are all about; instead of describing main effects once again. According to de Freitas and Mitcham (2012) cations K^+ and Mg^{2+} are known to compete with Ca^{2+} for binding sites at the plasma membrane and that high levels of K^+ and Mg^{2+} could potentially replace Ca^{2+}. This explaining the decrease in K^+ content at 60% Ca^{2+} treatment correlating with the Mg content mean in Table 4.5 since calcium dosage was higher than the recommended S1 concentration. Furthermore, the high concentrations of the divalent Ca^{2+} cation gives it a higher combining/bonding potential to other elements reducing the uptake of monovalent K^+ cations.

It was also observed by Huett (1994) that Leaf K^+ concentrations were generally reduced at low EC and a low K^+:Ca^{2+} ratio. In the case of the reduced K^+ at S2 treatment, despite the high K^+:Ca^{2+} the results showed that increased K^+ dosages in nutrient solutions did not necessarily result in a higher leaf K^+ content but could have been a result of climatic conditions like humidity which was observed by Sonneveld and Welles (2005). The authors found that the overall humid climate resulted in a decrease in the K^+ and Mg^{2+} concentrations in the leaves. This phenomenon is familiar in greenhouse crop production since there is high plant density in a small space therefore humidity becomes one of the most problematic greenhouse variables (Brechner and Both 1996). Thus increased or decreased Ca^{2+} cation concentration from the optimum 45% control recommended by Deckers (2004) evidently results in reduced K^+ uptake in Triple Play and Commander. Commander generally had higher K^+ across all treatments and this can be largely associated with its water holding capacity since its leaf structure reduces water loss hence a reduced Ca^{2+} and generally high leaf K^+ content compared to Ca^{2+} correlating with the Ca^{2+} and K^+ content values in Figures 4.1 and 4.2.



ANOVA	*F*-value	Pr > *F*	Significance
Cultivar*treatment	5.834	0.0048	**

** $p < 0.01$; ns, not significant at $p = 0.05$

Figure 4.2: The potassium composition of Triple play and commander cultivars at harvest as affected by cation ratios in the nutrient solution.

4.3.4 Magnesium content

The leaf Mg^{2+} content, showed no significant interaction between the main effects but different treatment means were observed as shown in Table 4.5. Leaf Mg^{2+} content was higher at 20% (S2) Ca^{2+} cation concentration in the nutrient solution and decreased as Ca^{2+} cation concentration increased. Mg^{2+} content at 45% (S1) and 60% (S3) Ca^{2+} concentration did not differ at all. The variation at 20% Ca^{2+} from 45% and 60% Ca^{2+} may be attributed to S1 and S3 having higher divalent Ca^{2+}: Mg^{2+} ratio meaning that more calcium elements were available to bond with other elements and be available, reducing the Mg^{2+} leaf content whilst for S2 there was more Mg^{2+} to Ca^{2+} hence more combining power and availability resulting in the increased Mg^{2+}. The results indicated that increasing the Ca^{2+} concentration from the standard 45% to 60% will not have an effect on the Mg content of the plants but may result in toxicity if unchecked. However, the reduction of the Ca^{2+} in the nutrient solution will increase the crop's Mg content, also noted by de Freitas and Mitcham (2012). Mg^{2+} has a predominant role as a major constituent of the chlorophyll molecule that is actively involved in photosynthesis (Silva and Uchida 2000). It is crucial to therefore create optimum solutions that promote the uptake of Mg^{2+} while cautiously avoiding toxicity and deficiencies (Cakmak and Yazici 2010). This also allows for manipulation of post-harvest quality traits stimulated by Mg such as lettuce colour (Cakmak and Yazici 2010), and furthermore that increased levels of available K^+ can aid in improving physical quality, disease resistance and shelf life of fruits and vegetables (Hoque et al. 2010).

Table 4.5: Magnesium tissue composition of Triple Play and Commander as affected by different cation concentrations in the applied nutrient solution ($P < 0.05$)

EFFECT	N	Magnesium (%)
Nutrient solution 1 (45%)	22	30b
Nutrient solution 2 (20%)	22	46a
Nutrient solution 3 (60%)	23	30b

Means within the column followed by different letters are significantly different at $P < 0.05$.

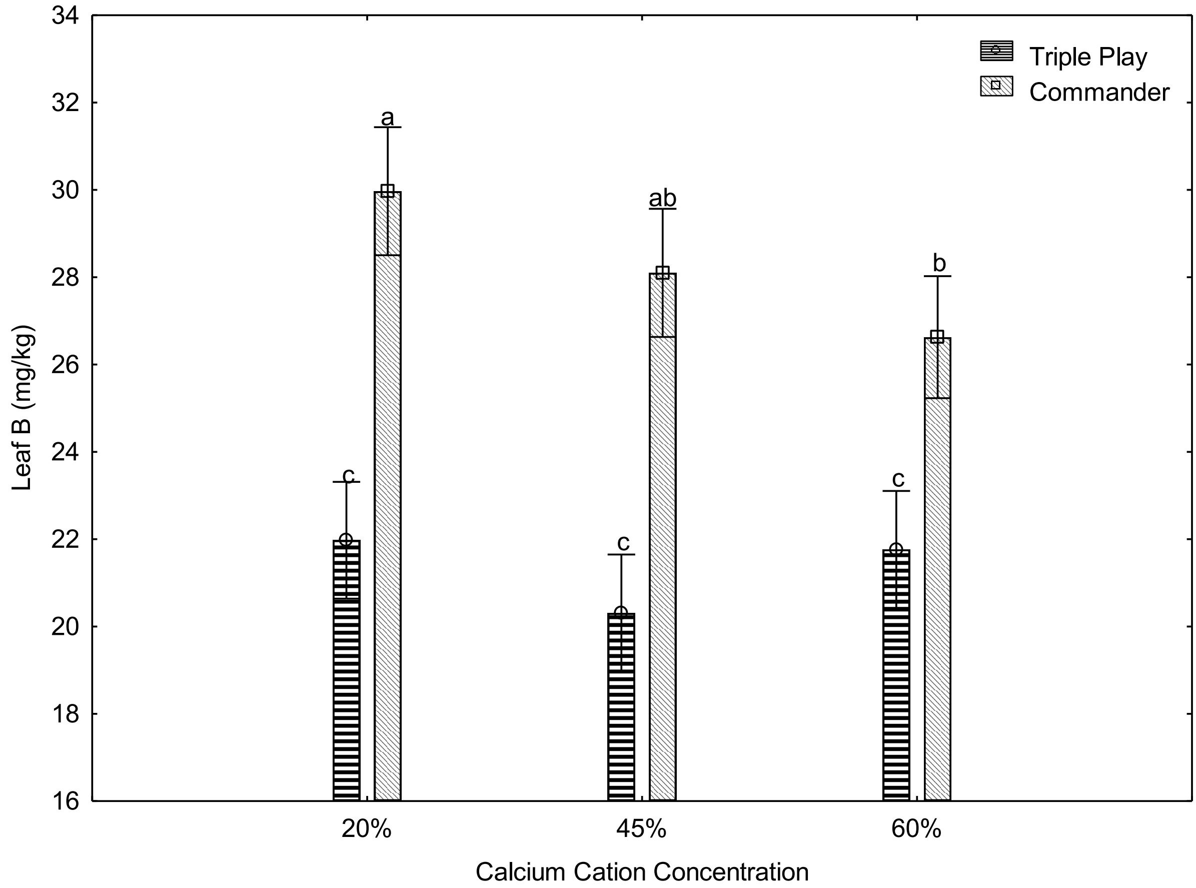
ANOVA	*F*- value	Pr > *F*	Significance
Treatment	58.649	0.0000	**

** *$p < 0.01$*

4.3.5 Boron content

Cultivar and treatment interaction effects on boron (B) leaf content were observed for both cultivars. Significant differences were observed between cultivars with Commander outperforming Triple Play across all treatments. There were clear differences in responses with commander having a higher B leaf content to tripleplay. Moreover commander, accumulated more B when Ca^{2+} cation concentration was increased from 20% to 45% to 60%, which subsequently resulted in a decrease in boron (B) content (Figure 4.3). Boron though a micronutrient and required in small quantities due to its toxicity has a structural role in the cell wall similar to that of calcium (Camacho-Cristóbal et al. 2008). According to Silva and Uchida

(2000), some functions of boron interrelate with those of nitrogen, phosphorus, potassium and calcium in plants (Libia et al. 2012). This correlates to the findings in this study that reduced 20% Ca^{2+} concentration resulted in an increased B content due to calcium deficiency and since B has similar functions to Ca^{2+} in the plant was therefore a substitute nutrient and vice versa can be true. The supply of micronutrients, namely Fe, Cu, Zn, Mn, B, Mo, and Ni, is very small in ratios to the other elements (macronutrients), so will perhaps have no negative effects (Sonneveld and Voogt 2009). This implies that boron content is not influenced by cation concentrations as observed (Figure 4.3) but could be affected by nutrient compositions as observed by Petridis et al. (2013). These authors showed that increasing boron decreased potassium available to the plants, which validates the results in Figure 4.3 where at 20% Ca^{2+} cation concentration, boron content was higher whilst potassium was lower. Commander outperformed Triple Play across all treatment concentrations with amounts above 26 mg/kg in comparison to boron amounts of less than 22 mg/kg for Triple Play. This variation in boron content between lettuce types could be the result of genetic differences which influence absorption of certain elements, maintenance and removal since it is passively absorbed (Samarakoon et al. 2006).



ANOVA	F- value	Pr > f	Significance
Cultivar*treatment	3.160	0.0495	**

** P<0.05

Figure 4.3: The boron composition of cos and iceberg lettuce cultivars at harvest as affected by cation ratios in the nutrient solution. Graph shows the interaction between the main effects with P < 0.05

4.4 Conclusions

Yield was not significantly influenced by applying different Ca^{2+} cation concentrations but due to different types of lettuce where differences in mean fresh weights were observed. The variation in mean fresh weight is a clear indication of how different lettuce types respond to different nutrient solution formulations. It is therefore crucial to understand how specific crops respond to nutrient solutions and identify the effect on the crop if it is growth, development, yield and or quality oriented. Furthermore, as was observed from the results that nutrient solution conditions, particularly Ca^{2+} cation concentrations, do have a significant effect on uptake of certain nutrients and if unchecked will result in either a deficiency or toxicity of the other nutrients with adverse effects on crop growth, development and post-harvest quality. Chemical properties of different elements should be understood as certain conditions will not only hinder uptake of one element but several elements with the similar properties. For instance Ca^{2} appears to have an inverse relationship with elements. Excess calcium levels can reduce a plant's uptake of other nutrients such as phosphorus, potassium, magnesium, boron, copper, iron, or zinc (Savvas et al. 2008). From the results, it is clear that nutrient solution formulation, that is cation concentrations and lettuce type should be carefully considered to ensure optimum nutrient availability and absorption for hydroponic lettuce producers.

In general, the study provides evidence that cation concentrations in hydroponic nutrient solutions have an effect on nutrient uptake during production and also dependede on lettuce type. It has further revealed that adverse effects on post-harvest characteristics can possibly be controlled through application of quality promoting nutrients in adequate concentrations that promote uptake of other essential elements necessary for optimum growth and development.

Further research is needed, however, to understand the effect of chemical characteristics in order to determine the minimum and maximum cation concentrations required to stimulate uniform uptake of all other nutrients to reduce deficiency and toxicity while enhancing yield and quality in lettuce production.

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CHAPTER 5

Effects of nutrient foliar application on yield and moisture loss during storage of hydroponically grown loose leaf red oak lettuce and rocket

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Abstract

Nutrient foliar application has been a method used to remedy nutrient deficiency and has proved effective and efficient during crop production. Its effectiveness and efficiency has been adopted for yield and quality enhancement. In this study the effects of foliar nutrient applications on yield and moisture loss during storage of hydroponically cultivated red oak lettuce (*Lactuca sativa* L. cv. Lollo Rossa) and rocket (*Eruca sativa* L. cv. Daytona) was evaluated. The trial was conducted in a climate controlled greenhouse where both varieties were grown in a closed re-circulating nutrient fim technique (NFT) system. Varieties were treated with three calcium based foliar solutions of calcium and nitrogen (CaN), calcium and boron (CaB), calcium and silicon (CaSi) and a control solution of water (W). Yield was obtained at harvest as fresh weight (FW). Rocket outperformed red oak with significantly higher FW across all treatments with $CaNO_3$ yielding highest at 100 g whilst unexpectedly CaB yielded the highest for red oak with 64 g across all treatments. Total moisture loss (TML) (%) was obtained after 5 days of storage as a primary predictor for shelf life. No significant interaction was observed but mean differences were observed for variety with red oak having the highest TML of 27% which correlated to the total weight lost for the same cultivar of 16 g compared to rocket. The study showed a greater significance effect of variety on yield and total moisture loss during storage than the effect of nutrient foliar treatments.

Keywords: calcium, variety, foliar spray, fresh weight, moisture loss, shelf life

5.1 Introduction

The need to intensify vegetable crop production for higher yields and crop quality has taken centre stage and vegetable producers have had to find ways to meet the demands through innovative approaches applicable to all crop production systems and crop species (Fageria et al. 2009). Many innovative approaches are already applied to hydroponic crop production systems as it is easier to administer and control since hydroponic systems are highly intensive and usually found within a small area. Lettuce grown hydroponically has faced challenges in the South African market because it has been compared to open field cultivated lettuce crops since they have been on the market much longer and set a standard in regards to quality and shelf life. In addition, hydroponic crop growers are still in the process of understanding the system to better optimise it for productivity (Du Plooy et al. 2012), hence the production of what has been deemed a crop of inferior quality. The innovative approach of nutrient foliar spraying to enhance crop quality should be seen as one of the solutions required by hydroponic crop producers in South Africa. Foliar fertilizer application has been found to be economic and according to Fageria et al. (2009). Achieved through visual foliar nutrient deficiency symptoms inspection and plant tissue tests, remedies plant nutrient deficiencies with the sole purpose of increasing yields and crop quality which have an overall effect on shelf life. Furthermore, according to Fernández and Eichert (2009a) there is abundant evidence showing the beneficial effect of foliar fertilizers in terms of improving crop quality and yields. When focusing on enhancing postharvest quality, several factors influence quality; in the case of leafy vegetables, texture (crispness) and colour (chlorophyll fluorescence) is important and in fruiting vegetables texture (firmness), shape (form), colour, taste and flavour will be key factors (Andrew Scofield 1999; Plich and Wójcik 2002; Agüero et al. 2008). To a greater extent all have the same underlying controllers which are water and nutrient absorption, translocation and efficiency as they control and regulate all metabolic processes responsible for plant growth and development which in turn influence yield and postharvest quality (Wurr et al. 2002; Arah et al. 2015). The benefit of application of nutrients via the leaves instead of the root system during growth and development of crops in a hydroponic system is largely because of the possible nutrient solution imbalances that can occur in a closed re-circulating hydroponic system. Once a nutrient solution has been in circulation, the specific pH and EC start to deviate, hence a direct application into the already circulating solution may enhance imbalances in nutrient ratios and affect uptake of specific nutrients (Lopez et al. 2003). Therefore supplemental foliar fertilization may be an important tool for sustainable and productive management of hydroponic crops.

With the ability to rectify nutrient deficiencies through foliar nutrient application, the technique has also been incorporated in boosting crop quality during growth and enhance post-harvest quality (Pardossi et al. 1999; Hilton et al. 2009). Understanding and optimization of plant nutrients for good crop quality is essential to achieve desired post-harvest quality and the application of foliar nutrient spray methods can be of aid in that regard as noted by Bacchus (2010) and Asad (2003). Key elements have been suggested to have an effect on crop quality which in turn influences shelf life. These elements due to their function in the plant have been singled out amongst others based on the extent to which they affect crop quality and they are calcium (Ca), boron (B) and silicon (Si) (Silva and Uchida 2000). Leaf vegetable freshness and shelf life is largely due to water content and the rate at which it is lost during storage. Specific elements like calcium, boron and silicon have been associated with enhancing postharvest shelf life because of their role in cell wall maintenance and strengthening (Silva and Uchida 2000).

The role of calcium in plant growth and development and particularly postharvest quality has been extensively scrutinized (Saure 1998; Napier and Combrink 2006; de Freitas and Mitcham 2012). Calcium (Ca) has a major role in the formation of the cell wall membrane and its plasticity, affecting normal cell division by maintaining cell integrity and membrane permeability (Silva and Uchida 2000). A lack of tissue Ca has again been associated with postharvest disorders like tipburn in leaf vegetables and blossom end rot in fruit vegetables (de Freitas and Mitcham 2012). Boron (B) is required in small amounts yet its deficiency has been found to be significant in affecting crop growth and development and overall quality (Blevins and Lukaszewski 1998). Research over the years has greatly contributed to a better understanding of the role of B in plants and this also resulted in a growing interest from farmers. The main functions of B relate to cell wall strength and development, cell division, fruit and seed development, sugar transport, and hormone development and therefore functions of B interrelate with those of nitrogen (N), phosphorus (P), potassium (K) and Ca in plants (Plich and Wójcik 2002; Camacho-Cristóbal et al. 2008; Petridis et al. 2013). Its deficiency results in symptoms like crooked and cracked stems in celery, browning and cracked midribs in cabbage pith and hollow stems in broccoli, cabbages and cauliflower (Silva and Uchida 2000). Less research of silicate (Si) in plant growth, development and yield has been conducted. Though overlooked, Si has been found in significant concentrations in plants which imply it has an effect in the plant. Smith (2011) states that silicon is deposited as silica in the plant cell walls, improving cell wall structural rigidity and strength, plant architecture and leaf erectness. It has also been shown to stimulate nutrient uptake and plant photosynthesis, decrease susceptibility to disease and insect damage, alleviate water and various mineral stresses and decrease the toxic effects of aluminium (Liu et al. 1996; Guntzer et al. 2012). The use of Si has been further associated in fungicide treatments (Menzies et al. 1992; Liu et al. 1996). However, Bacchus (2010) reported that application of silica spray had no statistically significant effect on lettuce fresh head yield, N uptake, plant sap nitrate concentrations and amino acid content. Conditions during these experiments were however far from that encountered by plants in a re-circulating NFT system in a temperature controlled greenhouse. Under these conditions, crop growth rate is optimal although the uptake of certain less mobile elements is limited may result in post-harvest losses.

The objective of the study was therefore to assess the impact of different foliar nutrient sprays on the yield at harvest, weight and total moisture loss of lettuce and rocket at storage from a re-circulating NFT hydroponic system.

5.2 Materials and Methods

5.2.1 Plants and experimental site

Seedlings of two commonly produced hydroponic crops; red oak lettuce (*Lactuca sativa* L.) and rocket (*Eruca sativa* L.) were supplied by Green Drop Farm and were transplanted on 1 September 2016 in a vertical hydroponic nutrient film technique (NFT) system. Before application of treatments plant health was visually inspected. The experiment was conducted in a climate controlled greenhouse at Green Drop Farm, Koelenhof, Stellenbosch, Western Cape, South Africa at a constant temperature setting of 20°C and a relative humidity range of 60% to 90%.

5.2.2 Preparation of foliar nutrient solution sprays and treatments

The rocket and red oak lettuce varieties were exposed to three foliar spray mixtures of $Ca_3(BO_3)_2$, Ca_2SiO_4, $Ca(NO_3)_2$ and a control of water. Three calcium (Ca) based solutions were prepared by dissolving; (1) 5 g L^{-1} of $Ca(NO_3)_2$ with EC of 2.73 mS cm^{-1}, (2) 3 mg L^{-1} of $Ca_3(BO_3)$ with an EC of 1.63 mS cm^{-1}, (3) 3 mg L^{-1} of Ca_2SiO_4 with an EC of 0.07 mS cm^{-1} into 2 L spray bottles filled with water. Treatment 4, serving as the control spray, consisted of 2 L of water with EC of 0.03 mS cm^{-1}. The total number of experimental units was 56, viz 28 for red oak lettuce and 28 for rocket respectively. At harvest, the samples were stored in a cold room for 5 days at 2°C, according to retailer recommendations.

5.2.3 Growing medium, treatment dosing and irrigation schedule

A total of 56 plant samples were used in this experiment with the roots submerged in an NFT system to allow a thin film of nutrient solution to flow past the root system. The particular system is a closed system where all the nutrient rich water is collected and recirculated in the system. The nutrient solution supplied was a slightly modified Steiner solution at an EC of 1.6 mS cm^{-1}.

Plant samples for foliar nutrient sprays were randomly colour tagged to allow application of correct foliar sprays to plant samples. Spraying was done once every week for four weeks during midmorning. The dosage of foliar nutrients per plant was five pulses which gave out 15 ml of treatment solution.

5.2.4 Harvest, storage and post-harvest conditions measurements and analysis

After four weeks the plant samples were harvested in the morning, the roots were removed and samples were not washed or chlorinated. After obtaining the head fresh weights, samples were packed in clear plastic bags that were sealed with the absence of any storage enhancing gases. They were stored in a cold room with temperature conditions of 2°C for a period of 5 days under 9 hours of fluorescent light exposure conditions.

The post-harvest quality in regards to freshness and shelf life was measured by obtaining the total weight loss (g) and total moisture loss (%) after 5 days of storage. In regards to total weight loss, the difference between FW at harvest and FW after 5 days of storage gave the total weight loss index.

Determining the total moisture loss (%) (Agüero et al. 2008),

TML (%) = FW AT HARVEST – FW AFTER STORAGE/ FW AT HARVEST X 100

The amounts of total moisture and weight loss were used as an indicator for shelf life for the two crops after storage. Total moisture loss was also used as the final indicator of freshness which is a significant postharvest trait affecting shelf life.

5.2.5 Experimental design and statistical analysis

The experiment was laid out as a complete randomized design (CRD) with seven replicates for each plant type. The data was subjected to Analysis of Variance (ANOVA) using STATISTICA software version 13. The Fischer test's least significant difference (LSD) (P = 0.05) was used for separation of means.

5.3 Results and Discussion

5.3.1 Yield

Evaluation of yield (FW) at harvest did not reveal a significant interaction between treatment and variety (Table 5.1). However, mean FW differences were observed for variety and treatments with rocket outperforming the red oak with highest fresh weight mean of 96 g and red oak with 59 g. This variation is largely due to above ground plant biomass where rocket is generally characterised with a high biomass/unit area largely due to its physio-morphological characteristics and growth rate (Guide 1994; Stefanelli et al. 2011). Furthermore, treatment differences were observed with CaB having the highest FW mean of 85 g which was unexpected but noted by Dell and Huang (1997) that boron deficiency inhibited root elongation by limiting cell enlargement and cell division in the growing zone of root tips and also that it inhibited leaf expansion lowering the photosynthetic capacity of the leaves. This would mean that the CaB treatment stimulated root expansion, increasing absorption efficiency of the plants hence explaining the elevated FW mean for CaB (Table 5.1). The other treatments, $CaNO_3$, CaSi however did not differ from each other significantly and from the control but had a relatively plateaued weight distribution with a marginal increase for $CaNO_3$. The slight variation between $CaNO_3$ and CaSi could be due to the availability and accessibility of N to the plants which is solely responsible for increased plant biomass and furthermore due to the different cultivar nutrient requirement characteristics, nutrient uptake, use and efficiency during the plant life cycle (Savvas 2003; Benton Jones Jr. 2004). This has revealed the extent to which nutrient foliar application can be an effective and efficient method in increasing yield if N had been administered in higher dosages.

Table 5.1: Effect of variety and treatments on fresh weight (FW) for red oak and rocket grown hydroponically. Significant differences between means are indicated by different superscript letters

ANOVA	F - value	Pr > F	Significance
Treatment	0.2548	0.8575	ns
Variety	14.5975	0.0000	**
Treatment*variety	1.4453	0.2413	ns

** $p < 0.01$ ns, not significant at $p = 0.05$.

Treatment	N	Fresh Weight Means(g)
CaN	14	76.07^b
CaB	14	85.29^a
CaSi	14	74.79^b
Water	14	76.29^b
Variety		
Red Oak	28	59.82^b
Rocket	28	96.39^a

5.3.2 Total weight and moisture loss during storage

From the results, treatment, variety and their interactions had no significant effect on total weight and moisture loss but a slight mean difference was observed for variety with rocket having a relatively higher total weight loss of 19 g compared to red oak with 16 g (Table 5.2). This mean weight loss variation could be the result of wilting and senescence which was observed to be higher in rocket lettuce due to its high respiration rates (Siomos and Koukounaras 2007). In the case of red oak, the opposite was true where the lower weight loss can be attributed to reduced senescence and wilting rates (Tsironi et al. 2016). Furthermore, marginal variation was observed for treatments with CaB having a high total weight loss mean of 20 g compared to other treatments. This was likely due to the possible boron toxicity effects as fertilization with boron was noted to result in toxicity as observed by Eraslan et al. (2007). It resulted in tissue membrane damage which increased the rate of wilting that correlated with the total moisture loss (27%) which was high compared to the control (Table 5.3). It is interesting to note the lack of a significant correlation between total weight loss and moisture loss between the lettuce varieties. Rocket had a lower total moisture loss of 22% compared to red oak with 27% but had a higher total weight loss of 19 g compared to red oak with 16 g. This lack in correlation can be the result of plant size where red oak characteristically has broader leaves resulting in a higher moisture loss rate/unit time compared to rocket hence the high moisture loss percentage for red oak variety (Table 5.3) (Nunes and Emond 2007).

Table 5.2: Effect of variety and treatments on total weight loss during storage for red oak and rocket grown hydroponically. Significant differences between means are indicated by different superscript letters

ANOVA	F - value	Pr > F	Significance
Treatment	0.6560	0.5831	ns
Variety	2.2413	0.1409	ns
Treatment*Variety	0.5745	0.6345	ns

ns, not significant at p= 0.05

Treatment	N	Total Weight Loss(g) Means
CaN	14	16.29^{b}
CaB	14	20.00^{a}
CaSi	14	18.14^{ab}
Water	14	16.21^{b}
Variety		
Red Oak	28	16.00^{a}
Rocket	28	19.32^{a}

Table 5.3: Effects of variety and treatments on total moisture loss during storage for red oak and rocket grown hydroponically. Significant differences between means are indicated by different superscript letters

ANOVA	F - value	Pr > F	Significance
Treatment	0.6126	0.6104	ns
Variety	1.0517	0.3107	ns
Treatment*Variety	1.1012	0.3587	ns

ns, not significant at p = 0.05

Treatment	N	Total Moisture Loss (%) Means
CaN	12	19.79^{c}
CaB	14	27.50^{a}
CaSi	13	28.71^{a}
Water	13	24.00^{b}
Variety		
Red Oak	25	27.68^{a}
Rocket	27	22.32^{b}

5.4 Conclusions

Variety and treatment interactions were not observed in this study nor was there a significant treatment effects on either yield or total weight (g) and moisture loss (%). However, mean variations were observed throughout the study for both treatment and variety on yield and total weight (g) and moisture loss (%). The objective was to assess the extent to which nutrient foliar application could be applied not only for remedying nutrient deficiencies but enhancing yield and quality. From the mean variations, it is evident that nutrient foliar applications can be used as a tool to enhance yield and moisture holding capacity of crops for better quality retention during storage. This study has further revealed the effect of variety differences in regards to yield and shelf life which should be taken into consideration when formulating foliar treatments to enhance water retention capabilities for reduced water loss. From the results, a more surgical analysis is required to better understand the complex scenarios surrounding the delivery of foliar-applied nutrients to plant organs taking into account toxicity effects (Begoña and Jesús 2010). Research has been conducted and reveals complexities such as how foliar-applied urea solutions are highly permeable and the resultant N metabolites are easily transported from mature leaves to sink organs observed by Stiegler et al. (2011). Furthermore, how boron can be absorbed by leaves at rates almost equivalent to urea, but have limited mobility within many plant species making their efficacy strictly local but in species with high phloem boron mobility, boron foliar application results in increased absorption and rapid movement to sink tissues (Brown and Shelp 1997; Blevins and Lukaszewski 1998; Will et al. 2011). These findings show the extent of plant variety in response to foliar fertilizers and should be understood for effective and efficient application of leaf nutrient solution for enhanced yield and shelf life.

5.5 References

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Chapter 6

Summary and General Conclusions

The ability to control plant growth and development variables (light, relative humidity, temperature, nutrient fertilization) in a hydroponic system has given it comparative advantage over other crop production systems resulting in its adoption on the South African agricultural sector. Extensively used in horticultural crop production of leaf vegetables, herbs, fruits and flowers and apart from increased productivity, sustainable and economic practices, soilless cultivation requires strategic and precise management to reap the benefits of the system. The 21st century has ushered a shift from the need to increase crop productivity to the demand for better crop quality resulting in further research being undertaken to understand how to optimize for better crop quality without compromising on yield. Research conducted in that regard is to give aid and information to hydroponic crop farmers on how to better control and manage these systems in order to improve crop quality. Hence the aim of this study was to assess the impact of controlling and managing nutrient solution concentrations and light intensity levels on postharvest quality of lettuce varieties (*Lactuca sativa* L.) which involves texture, colour, shape and nutrient content in a hydroponic crop production system and how foliar fertilization maybe applied to enhance quality traits.

Due to the climatic characteristics of South Africa with relatively long photoperiods, much of hydroponic crop production in South Africa does not require supplemental lighting and is mainly done under some sort of infrastructure which is usually cladded in glass, plastic or shade nets which results in reduction of light intensity that adversely impacts crop growth and development. Due to the sensitivity of plants to different wavelengths, the study focused on light conditioning in hydroponic systems to assess the impact it has on postharvest quality. The trials were conducted in a glasshouse at the Department of Agronomy at Stellenbosch University with two lettuce (*Lactuca sativa*) types, iceberg and cos. The plants were completely randomised (CRD) and exposed to three different light intensities (LI), control of 450 µmol m^{-2} s^{-1} (19.44 mol m^{-2} d^{-1}), 60% of control at 270 µmol m^{-2} s^{-1} (11.66 mol m^{-2} d^{-1}), 40% of control at 180 µmol m^{-2} s^{-1} (7.78 mol m^{-2} d^{-1}). The results showed significant light treatment and cultivar effect on yield with decreasing fresh weight as light levels decreased from the control. With regard to lettuce type, cos developed broader leaves, increasing its fresh weight index. Post-harvest traits such as chlorophyll content which affects lettuce colour was significantly impacted by light intensity where an increase in chlorophyll content was observed at 60% light intensity with cos having a significantly higher chlorophyll index than iceberg lettuce. With regards to texture, effect of light intensity and cultivar interactions on the texture of cos and iceberg lettuce was significant ($P<0.05$) with a significantly high crispness quality for both cultivars as light intensity decreased. With regard to plant height which affects the shape (form), the effect of light intensity and cultivar interaction on plant height of both cos and iceberg cultivars was observed with significance at $P < 0.05$. LI levels had a significant effect on the plant height for both cultivars to a greater extent iceberg lettuce measuring at the same height with cos lettuce at 40% LI and control LI. The results showed the interaction effect of treatment and cultivar resulting in physiological changes that affected quality variables significantly.

Soilless cultivation of lettuce or any other crop is largely done in a nutrient filled water media and precise conditions are applied to enable uptake of all nutrients required for plant growth and development. This entails optimum pH level, oxygen level, water temperature and electrical conductivity (EC). The study focused on control and management of nutrient solution cation concentrations. The trials were conducted at the Department of Agronomy at Stellenbosch University with two lettuce (*Lactuca sativa*) types, iceberg and cos exposed to three different cation concentrations derived from standard Steiner nutrient solution using calcium with control Ca^{2+} 45% (S1) compared to low Ca^{2+} of 20% (S2) and high Ca^{2+} of 60% (S3), all at an EC of 1.30 mS cm^{-1} in a drain to waste system. The different calcium cation concentrations of the nutrient solution showed no significant cultivar and treatment interaction on yield though increasing cation concentration alone showed a significant mean weight gain from the control. Yield variable was unaffected by the different Ca^{2+} cation concentrations, but cultivar had a significant effect on yield with Triple Play (cos) having a mean fresh weight of 547 g and Commander (iceberg) of 319 g although not statistically significant. Leaf mineral content was affected by both cultivar and treatment interaction with Ca^{2+}, K^{+} and B showing significant increases and decreases in that regard. A full chemical analysis for micro- and macro elements indicated that key nutrients responsible for crop quality (calcium, boron and potassium) were significantly affected by the treatments. Calcium cation concentration showed no statistical significance effect on magnesium uptake when either increased or decreased. From these results, it is clear how formulations of nutrient concentrations will impact uptake of quality stimulating nutrients as well as nutritive content of the crop. Therefore without affecting productivity, timely increases and decreases in cation concentrations in sync with plant growth and development, nutrient needs can be controlled and managed to enhance specific quality attributes of crops in a hydroponic system.

The application of foliar fertilizers has been in practice for decades as it has been used as a tool to supplement nutrients for nutrient deficient crops. The same concept has been applied to investigate supplementing specific nutrients for the purpose of enhancing crop quality as was investigated in this study. The trial was conducted in a greenhouse at Green Drop Farm where two crops, rocket (*Eruca sativa* L.) and red oak lettuce (*Lactuca sativa* L.), were grown in a re-circulating NFT system. The crops were treated with three calcium based foliar solutions of calcium and nitrogen (CaN), calcium and boron (CaB), calcium and silicon (CaSi) and a control solution of water (W). The results showed a significant treatment and cultivar interaction with regards to fresh weights and differences between treatments and cultivar was also observed. Differences from the control treatment showed an increase in FW when CaN and CaB were applied whilst marginal decrease in FW from the control was observed when CaSi was applied. This is possibly the result of nutrient physiochemical and mobility characteristics in a plant and plant nutrient requirements. Furthermore, total weight and moisture loss which plays a significant role in shelf life revealed that apart from significant cultivar effect, foliar fertilizer application of quality stimulating nutrient did have a significant effect, resulting in differences in total weight and moisture loss as observed for CaB which resulted in high moisture loss percentage followed by CaSi. The least was with CaN, whilst with regards to weight, significant weight loss was observed in the same order. Therefore with the application of foliar treatments, the extent of the efficacy was largely governed by cultivar and treatment composition combined, which when managed correctly will yield expected results.

Conclusion and future research

In light of the results in this study, it is evident that controlling and management of crop growth and development variable particularly external conditions such as those investigated, light intensity and nutrient concentrations and use of supplemental foliar fertilizer application can have both positive and negative effects on postharvest traits. The results revealed the need for more research to focus on cultivar physiochemical and genetic characteristics and how they are affected when plant growth and development variables are adjusted for quality enhancement purposes. This should be able to identify specific markers that correlate to quality traits in a cultivar and condition the variables to stimulate those markers for a specific response and hence multiply the effect. Therefore knowledge of the extent to which hydroponic management of plant growth and development variables influences crop responses with regards to postharvest would improve significantly crop quality.